Children’s Multiple Representations of Air\textsuperscript{1}

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Abstract

This paper reports research on children’s multiple external representations of air and the particulate nature of matter. The process of externalizing one’s understanding helps to strengthen and develop ways of seeing the world. Students engaged in a process of representing their ideas across multiple systems cultivate a stronger, richer understanding of the content. In addition, such a multi-modal exploration provides the researcher with a diverse array of ways through which children view science concepts. In the present study, 8th grade students attending an urban public school expressed their understanding of air as a substance through four primary systems of representation: oral language, drawing, stop-action movie making, and the construction of physical artifacts. Results suggest a relationship between the conceptual aspects of air externalized and the system of representation under investigation. Specific contexts evoke specific aspects about air. While we take care not to generalize these findings, the results emphasize the importance of providing students multiple opportunities for inventing ways of expressing their ideas about science as means for developing a deeper understanding of scientific concepts.

1.0 Introduction

The study reported in this paper investigated the use of multiple systems of external representation in explorations of fundamental science concepts, in our case air and a particle model of matter. Previous studies in mathematics and science education research have been carried out in the area of multiple representations (Brizuela, 2004; Brizuela & Ernest, 2007; Goldin, 1998; Lehrer & Schauble, 2000a, 2000b; Nemirovsky, 1994; Pozo & Gómez Crespo, 2005; Johnson, 1995; Zhang, 1997; Zhang & Norman, 1994). However, the present study strongly emphasizes the role of production of external representations – spontaneous, student-generated and sometimes idiosyncratic representations – across multiple systems, a topic receiving less attention in the science education literature. Previous research has documented students generating insightful representations about science concepts in hybrid systems (e.g., animations or physical artifacts; see Martí & Pozo, 2000). For example, through the process of generating stop-action movies, middle and high-school students have represented rich understandings about topics such as parabolic motion, which have usually been found to be difficult (Church, Gravel, & Rogers, 2008). However, hybrid representations such as stop-action movies are rarely used in typical school science activities, and this deficiency could be limiting students’ abilities to represent complex and intricate understandings. Bamberger (1991) notes:

Children who are most successful, even virtuosos, at using their hands to build and fix complicated things in the everyday world around them are often the same children who are having the most difficulties learning in school. These children are frequently identified as having trouble in working with common symbolic expressions – numbers, graphs, music notation, written language – the “privileged languages” that form the core of schooling. With the emphasis in schooling on symbolic knowledge, it is not surprising that attention focuses on what these children cannot do, and it is also not surprising that the school world sees them not as virtuosos but as “failing to perform.” (p. 38)

Bamberger’s message goes beyond gaining symbolic knowledge: students engaged in multiple ways of representing their knowledge possess greater opportunities to develop their
understanding and their ability to express that understanding in new ways. Additionally, the researcher gains multiple ways of viewing the student’s understandings. While externalizing ideas through multiple systems likely improves one’s understanding of symbolic representations, it can benefit an individual’s conceptual understanding as well. Therefore, the present study aimed to give students opportunities to explore a common, yet quite complex, concept—air and a particle model of matter—using multiple means of representation. It was our hypothesis that students would display different aspects of understanding in different systems, while concurrently developing their understandings of air and the particle model of matter.

The particular content topic for this study, air as a substance, was chosen for a multitude of reasons. Nearly eight decades ago Piaget (1930/2001) reported studies involving children’s conceptions of air and wind. He found that young children often associate air with the presence of wind or objects moving because of air currents, such as the leaves on trees. From this point of view, there needs to be some change in a current state (a dynamic state) in order for air to be recognized. Children as young as 5 years old are familiar with the term “air”, thus, one can argue that children have encountered the idea from a very young age. While air is used in everyday, nonscientific conversations with great frequency and can even cause observable effects (e.g., moving tree leaves), it remains "unseen," which can lead children to develop alternative explanations for effects caused by air based on their prior knowledge. These ideas are often called "naïve" and describe the spontaneous knowledge children posses (McCloskey, 1980, 1983; Vosniadou, 2002). Children’s naïve ideas about air (in both static and dynamic states) coupled with the unseen nature of air make it a rich topic for researching multiple modes of representation in children’s making sense of science. Unseen agents (e.g., air, gravity, sound) are conceptually rich topics because while we can observe the effects of such agents, we must make explicit the mechanisms of change in some other way. For example, in order to explain how a shift in air pressure in a room can cause a door to close, a child must make explicit the mechanism he or she believes was responsible for the action. In the process of generating this explanation, the researcher can gain a unique perspective into how the child makes sense of the situation. With unseen agents, we gain a unique window into not only how students make sense of science concepts, but how they choose to externally represent these concepts. Thus, the unseen nature of air makes it a compelling topic for investigating relationships between conceptual ideas and external relationships. The study presented here is grounded in a theoretical framework of the role of multiple external representations in the development of scientific understanding.

1.2 Language of science is multiple representations

The language of science is multiple representations; scientists use drawings, graphical notation, mathematical symbols, written language, oral language, and models to communicate their findings and to fuel future discovery (Chapman, 2000; Garcia-Mila, Andersen, & Rojo, 2009) The domain of science concerns itself with generating models of new concepts and the ways in which these models are shared and discussed is through multiple representations. Constant testing and refinement of said models involves re-representing the ideas across a variety of expressive media. Thus, the ways in which scientists communicate ideas is intimately dependent on multiple representations. For example, we have overwhelming empirical data suggesting that two massive bodies are attracted to each other by a gravitational force. Before the apple fell on Sir Isaac Newton’s head, gravitational force existed, but it was not until he
developed a mathematical model for this concept that it could become as important in the scientific discourse as it is today. Models and the ways of representing these models are fundamental elements of science, however, defining the term model relative to children’s ideas about science is an arduous task. The term model has taken on numerous meanings, depending on the domain from which the term is considered (Lehrer & Schauble, 2000a; Justi & Gilbert, 2000; Stewart & Golubitsky, 1992; Vosniadou, Skopeliti, & Ikospentaki, 2005), but that does not preclude us from articulating the ways in which scientific models are similar and dissimilar to the models children use when making sense of the natural world.

Children hold models much like scientists, especially those of antiquity. Aristotle believed that heavy things fall faster; Galileo revised that model (by rather famously dropping balls from the Tower of Pisa); and Newton derived a mathematical relationship that elaborated on Galileo’s model (Gribbin, 2002). The history, albeit brief, of gravity highlights how models are tools for thinking about how the world works. Stewart and Golubitsky (1992) describe the scientific method as deeply dependent on models (i.e., mathematical descriptions), that “capture essential fragments of how [scientists] think the world behaves” (p. 2). They argue that scientists use these models to develop theories that can be tested with hypothesis and experimentation. The models are revised in an iterative fashion until the theory and experiment agree (which is a rarity). Thus, models are dynamic, evolving tools that scientists use to make sense of the natural world. It is reasonable to suggest that children, too, develop models (although hardly scientific, in the stricter sense) to help them understand how the world works. Lehrer and Schauble (2000a) argue that children can be considered as natural modelers, who are able to see how certain ways of conceptualizing phenomena are useful in multiple contexts. This is not to suggest that children hold coherent, generalized models in the scientific sense, but rather that children develop certain ways of making sense of phenomena that can be treated much like scientific models. The process of developing and refining models is inextricably linked to the systems of representation through which the models are expressed. In other words, inherent in the revision of models is the development of new ways to represent the ideas of science. The importance of modeling in science is widely recognized, and the way in which models are developed is through the use of external representations, which are the focus of this paper. When scientists are debating the intricacies of phenomena, they are arguing about graphs, mathematical equations, drawings, diagrams, written language, spoken language, and even gesture. In other words, scientists “talk” through a multitude of representations. For children, the external representations that they produce are often idiosyncratic and non-normative, however, they are important elements in the process of constructing scientific understanding. Therefore, models and representations are fundamentally different, but both intrinsically important to understanding how the world works. In summary, an examination of the role representation plays in how children use models (either consciously or unconsciously) to construct knowledge is crucial to the field of science education.

1.3 Process vs. Concept

The term representation as used herein namely refers to externalizations (i.e., events or objects perceivable by others). External representations have an important duality that make them a valuable lens through which to analyze how children develop understanding. The distinction is based on an important duality captured in different ways by different theoretical frameworks (see Breidenbach, Dubinsky, Hawks & Nichols, 1992; Douady, 1997; Ferreiro, 1994; Sfard, 1991; Tolchinsky-Landsmann & Karmiloff-Smith, 1992) between process (or tool,
in Douady’s terms) and object. From one perspective, the operations or actions required to represent a scientific or mathematical concept can be considered as a process. For example, in mathematics, a function can be seen as a “method for getting from one system to another” (Skemp, 1971, p. 246). This definition of function reflects an operational conception (Sfard, 1991); functions are considered as a process through which to achieve some transformation. For children developing an understanding of functions, the approach to the concept is from a process perspective, where the function is a tool (Douady, 1997) for doing something. Similarly, consider the development of written language. A child’s understanding of written language is a constructive process, where the use of idiosyncratic inscriptions and conventional letters are tools for conveying ideas (Ferreiro, 1994). It is not until the child has developed sufficient understanding of the written language system that they can begin to consider words as objects that represent ideas that can be reflected upon. Sfard (1991) argues that (in mathematics) “the majority of ideas originated in processes rather than objects” (p. 11). For children, the development of knowledge and of a capacity for representing understanding in various systems begins as a process as well.

Children grow up in a world that is filled with conventional and idiosyncratic systems of representation. They experience oral language, written language, graphs, gestures, pictures, moving-pictures, and a myriad forms of representations. Once they have developed the semiotic function, they begin to experiment with and refine how they represent their understandings. Living immersed in a world full of symbols and signs, it is to be expected that this process of representing will be influenced by exposure to and interactions with various forms of representation—representations laying in a world “external” to the child and capturing a historical trajectory of some nature on the part of humankind. Furthermore, the process of representing as essentially referential-communicative (Tolchinsky-Landsmann & Karmiloff-Smith, 1992) yields a physical artifact or action perceivable by others (e.g., gestures, writing on paper).

These artifacts become conceptual objects in their own right (Olson, 1994), whereby the object, while being a representation, is perceived as the referential concept. This structural conception (Sfard, 1991) of representations allows the individual to reflect upon the concept as embodied in the external representation. Therefore, external representations can be both a process and conceptual objects. Furthermore, establishing a strict dichotomy might not be very helpful, because students involved in explorations of new ideas likely transition between process and object aspects of representation as they construct an understanding. Representations as conceptual objects are pivotal in the development of thought, as placing an idea in the external world allows for reflection and evaluation of one’s understanding (Kaput, 1991). By making knowledge explicit through a process of externalizing ideas, children strengthen and develop their conceptual understanding (Lehrer & Schauoble, 2002; Schliemann, Carraher, & Brizuela, 2007; Tytler & Prain, 2007). In addition, the artifact (i.e., conceptual object) provides the researcher with a perspective regarding what the child knows (Kaput, 1998). Eventually, the external representation becomes a fundamental element of any understanding. Thus, representation is a process whereby children explicate their knowledge, resulting in a conceptual object that is part and parcel of thought. In the context of children’s understanding of science, the process and object characteristics of representation should be concurrently considered, as both help the child reason and think.

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1 At around 18 months of age, according to Piaget and Inhelder (1966/1969).
1.4 Representations as thought amplifiers

The signified and signer (de Saussure, 1959; Piaget & Inhelder, 1966/1969) are hallmark constructs in Piaget’s notion of the semiotic function. Early signs of the semiotic function also indicate progress toward achieving a “Copernican revolution” (Piaget & Inhelder, 1966/1969), wherein children recognize that they are but one object within a larger universe of many independent objects. In other words, this notion suggests that children undergoing such a revolution begin to understand that there is a universe beyond that which they can directly perceive. This process is also referred to as decentering, and it affords individuals the ability to represent. Decentering allows a child to recognize the existence of a causality that is “both localized in space and objectified in things” (Piaget & Inhelder, 1966/1969, p. 13), which forms the foundation from which she will develop reflective and, eventually, abstract thought. Thus, the act of representing (i.e., the process) helps us to organize and refine our ideas (Kaput, 1991), and the artifact (i.e., the object) becomes a vehicle for thought. Moreover, the representations we produce are encapsulated within our understanding of the natural world. The perspective that representations are essential to formal thought is primarily a Piagetian construct (Piaget & Inhelder, 1966/1969), however, the idea has much broader implications. In the world of mathematics and science, the use of multiple forms of representation (both internal and external) is heavily relied upon for the general activities of professionals in the field. Producing representations has an effect on the young child, but externalizing knowledge also has an effect on scientists who are fluent with several systems of representation (e.g., mathematical notation, graphical notation, written notation). More broadly, external representations have also been found to influence entire domains of knowledge, such as with the introduction of the Feynman Diagram to the field of theoretical physics (see Kaiser, 2005; Schweber, 1986). Richard Feynman’s proposal of this new representation shaped the thinking of quantum dynamics researchers, which illustrates the power of representation in a domain such as science. The process of a scientist introducing representations and refining them to optimize their purpose is related (in some sense) in children’s attempts to represent new ideas.

1.5 Progressive symbolization

When a child writes or draws something, that externalization, we assume, is linked to an understanding in the mind. In other words, the signified is linked to the signer by some “associative bond” (de Saussure, 1959, p. 66). However, once a representation becomes objectified (e.g., in a written form on paper or an intentional gesture), the link between the conceptual object and the understanding needs to be re-constructed. Such is the case for children adopting conventional systems of representation such as written language or mathematical notation, for example, what a negative sign represents in reference to velocity and motion (Nemirovsky, 1994). Children must construct a link among the conventional notations such as letters and numbers, but they must also continually re-construct the association between whatever idiosyncratic representation they produce and their own understanding as well (Goldin & Kaput, 1996; Lehrer & Schauble, 2002). There is a process of production and realignment that deeply impacts how children represent their ideas, and the work of diSessa, Hammer, Sherin, and Kopalkowski (1991) on children’s inventing graphing highlights this process.

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2 Which Piaget would argue is a long, arduous process that may begin in the semiotic stage, but continues to occur well into the pre-operational stage (Piaget & Inhelder, 1966/1969) as well as beyond, including adulthood.
In a relatively short intervention (five class sessions) with sixth-grade students in Oakland, California, diSessa et al. (1991) indicated that children have a natural ability to invent and critique representations. Students were presented with the following scenario:

* A motorist is speeding across the desert, and he’s very thirsty. When he sees a cactus, he stops short to get a drink from it. Then he gets back in his car and drives slowly away. (diSessa et al., 1991, p. 125)

Each student was charged with putting something on paper that described the motion of the motorist. The students’ first attempts at representing the scenario yielded idiosyncratic notations based on lines, dashes, dots, and other relatively generic shapes. Discussions about each notation lead to realizations by the students that more than one dimension needs to be included in a representation of the motorist’s trip. For example, some of the initial drawings only represented changes in speed without consideration of changes in time or distance. Through revisions of their original notations, the students developed more complex notations showing distance and time. In each successive revision, the conversations between the students and the teacher served as a way for each individual to find some meaning in the newly produced form. Each student needed to match the specific version of the representation with his or her understanding of the motorist’s path through the desert. Eventually, the students came to an agreement on a final representation for speed, distance, and time that was a position versus time graph—a conventional method for representing motion. diSessa et al.’s (1991) work highlights two critical elements of children inventing representations. The first is that through invention and critique of representations, students can develop and appropriate (when mediated by an expert, in this case the teacher and researchers) conventional means of representing information (see also Enyedy, 2005). The second important element to this episode is that any externalization of knowledge requires an accompanying connection between the artifact and each individual’s understanding. Even when the individual produces the representation (as opposed to viewing one that someone else produced), he or she critiques the artifact, and inherent in that critique is the creation of an association between the external artifact and the ideas the individual holds about the particular situation.

Many researchers have shown that children have a powerful ability to critique representations (diSessa et al., 1991; diSessa & Sherin, 2000), and such evaluations of the artifact are central to the reconstruction of the link between the object and the signified. Bamberger (2006) proposed that for musicians and children learning music, “performances (both silent and out-loud) involve a process of active, sense-making occurring in real-time” (p. 70). While Bamberger’s work refers to music, we believe it is pertinent to the current discussion.

Consider the externalization of knowledge to be a performance, whereby the child is demonstrating some aspect of knowledge. This notion of active, real-time sense-making accurately describes how the child produces and reflects upon a representation, as to rebuild the link between idea and object. A second attempt to reproduce the same representation will likely reflect this newly formulated association and may result in a more complex or refined representation. This “second generation” representation undergoes the same re-linking process described in a “progressive symbolization” (Enyedy, 2005; Lehrer & Schauble, 2002) process. The question that progressive symbolization attempts to address is how “the process of

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3 The term notation is used in reference to markings on paper that students generated in the diSessa et al. (1991) study. Notation (which is a form of external representation) is the term used by diSessa et al. and in the interest of consistency we have chosen to use the term in this section. In the remainder of the paper, the term representation is used as to encompass notations, inscriptions, and other commonly used terms.
progressively refining one’s representation of some aspect of the world can contribute to a deeper understanding of a domain” (Enyedy, 2005, p. 428). Alternatively, Karmiloff-Smith (1990) proposed representational redescription as a similar construct, where students undergo developmental changes whereby they represent elements of the same knowledge in progressively more abstract ways over time. Children regularly engage in such progressive or re-representational activities, particularly in mathematics and science learning, which leads to increasingly complex understandings of the particular domain of study (Lehrer, Strom, & Confrey, 2002). An example is the lengthy process of children coming to appropriate the conventional forms for writing numbers. Although they may begin to use the forms from a very early age (around 3 in most settings in which they are able to interact with these forms), it is only around the age of 10 that children truly and deeply grasp all the nuances underlying the decimal place value written number system. This lengthy process is grounded in continual redescriptions of the written forms to children’s understandings of number and the logic of the system. Underlying this process of change is the notion that children are iteratively or cyclically producing and refining representations of knowledge, and the refinement is heavily influenced by the ability of the child to re-construct a link between object and idea. For example, children inventing methods for mapping height showed a progression from overhead representations to eventually creating and adopting topographical lines to represent changes in height (Enyedy, 2005). Similar to how students re-invent graphing (diSessa et al.), each successive attempt to refine the representations resulted in complimentary conceptual gains such that the new representations matched the understandings of the children. The act of representing and re-representing to refine knowledge (Waldrrip, Prain, & Tytler, 2008), and to define the symbols themselves, is analogous to what scientists and mathematicians do in their respective domains.

In a domain such as Theoretical Physics, efforts to generate new models that simplify the representations of concepts are a driving force for the field. In doing so, scientists utilize conventional systems of representation as well as introduce new elements to better describe the concept, such as with the Feynman Diagram. Children engaging in progressive symbolization go through a similar process. As they objectify knowledge, they will slowly incorporate and appropriate elements from conventional systems of representation. Eventually, children come to learn the conventions and how they are used. The iterative process described is an example of how externalizing knowledge can serve as a thinking tool: by becoming object, it allows us to reflect on them, verify our thoughts, and contrast between different understandings and representations. It also highlights the importance of conventional systems of representation, the origins and development of which are deeply influenced by cultural factors.

1.6 The role of culture in representation

Discussing representation as though it were a singular mechanism, uninfluenced by factors in the environment or body is naïve. In fact, the development of the ability to represent knowledge is shaped by a multitude of factors, not least of which is culture. The use of culturally-developed representations (such as arrows to depict motion, or written language to describe an observation) is often present in children’s representations of science, which illustrates how they incorporate cultural ideas and artifacts into their externalizations. Vygotsky

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4 Karmiloff-Smith’s (1992) *representational redescription* model is primarily concerned with internal representations, however, external notations play a role in the construction of such internal representations, thus this construct is relevant in the context of this study.
(1978) suggested that children develop understanding through processes that are mediated by both adults and artifacts of a particular culture. In other words, “the special quality of the human environment is that it is infused with the achievements of prior generations in reified form” (Cole & Wertsch, 1996, p. 2), and these achievements are what mediate the development of understanding in children. Individuals belonging to a particular cultural group will develop means of expression and artifacts that embody shared-meaning. Vygotsky suggested that these tools include “various systems for counting; mnemonic techniques; algebraic symbol systems, works of art; writing; schemes, diagrams, maps, and mechanical drawings; all sorts of conventional signs, and so on” (Vygotsky, 1981, p. 137). Such products of culture become conventional means of representing and acting through a process of finding shared meaning. In other words, a desire to communicate will drive a culture to invent ways of talking, writing, or even gesturing that all members can use and understand. One could make the case that all representations embody, on some level, aspects of their native culture because they serve as vehicles for interactions among individuals (Cole, 1996; Nelson, 2009; Vygotsky, 1978). The conventional ways of representing ideas deeply impact how children come to express their knowledge, and language is considered to be one of the prime examples of a cultural invention that mediates representations of understanding. This is why Vygotsky put language at the forefront of his theory of development, for language is what opens the doors for many children to begin experimenting with externalizations (Vygotsky, 1962).

When children begin developing the ability to represent ideas, through language or any other form (i.e., gesturing or drawing), they are doing so within a cultural context laden with conventional systems. And while learners may not master the conventions, these cultural standards influence how children spontaneously represent knowledge at younger ages and how they eventually come to master and appropriate (granted, each individual with his or her own particular signature and flavor) a conventional system such as written or oral language, or the written number system. The conventional systems serve as a gateway for learners to begin to understand the more complex and abstract conceptions that are prevalent in their particular culture. While culture shapes representations, it also shapes the use of these tools and the nature of knowledge. Conventional systems are developed by cultures as they negotiate a shared meaning about a particular concept (Confrey, 1991). Convergence of meaning amongst members of a culture (i.e., engineers or physicists) results in such negotiations which center on the external representations of the concepts in question (Confrey, 1991; Roth & McGinn, 1998). Integrated within these negotiations are decisions and agreement about what symbols are to be used to represent which conventional ideas. Thus, those ideas that are accepted by a particular culture may be added to their collection of conventionalities. In fact, representation systems such as written language and the mathematical notation systems are products of human attempts to describe and share meaning over centuries of development. Thus, the role of social interaction and negotiation plays a crucial role in how conventional representations come to be, as well as in how students come to know and use these systems in order to express their ideas.

1.7 Representations as the centerpieces of negotiations of meaning

It can be argued that a concept as we know it (e.g., gravity) does not exist without its accompanying representations. The scientific concepts humans have agreed upon to be “true” are dependent on the representations of these concepts, because these representations serve as the focal point for the negotiations that lead to accepted meaning. When a scientist discovers a new
phenomena (which we acknowledge can impact the world before a representation of that concept has been developed), he or she constructs a means for communicating this new idea to the scientific community. For the domain expert (i.e., scientist), such a representation will likely include elements from conventional systems such as graphs or mathematical notation. Once the idea is objectified in the artifact, conversations regarding the validity, robustness, and accuracy of the proposed concept eventually decide its fate. For some, the representation chosen by the discoverer may not be suitable and, thus, may be modified to satisfy concerns. Others may accept the representation but challenge the methodology through which the evidence for such a phenomenon was generated. For example, when Einstein proposed his special theory of relativity, which revealed the equivalence of mass and energy with the famed $E=mc^2$ algebraic representation, it was of limited impact on the field of physics (Gribbin, 2002). It is inaccurate to say that his contemporaries did not understand his theory, but the ideas did not make a significant impact until translated into four-dimensional geometric terms (Gribbin, 2002). At the time, algebraic notation and geometric notation were both conventional in science; however, it took some negotiation and discussion before the field came to unanimously accept the theory as accurate and powerful. At the center of the discussions around newly introduced concepts is an externalization of some knowledge, and eventually the community will come to either reject the idea or find shared-meaning in the representation which would elevate the idea to a level of consensual knowledge (Kaput, 1991). We need to call attention to the inherent pattern existing within this negotiation of meaning (Confrey, 1991). Progressive symbolization, as described above from the standpoint of the individual child, can now be expanded to include the role of social interactions in learning to represent. For the community, the external representation helps to organize and refine a shared understanding, while each individual must reconstruct his or her associations between the representation and the underlying concept. Therefore, the inherent pattern found in instances of meaning arriving from negotiation is present within the individual and within cultural contexts.

2.0 Defining representation

Representation is a somewhat ubiquitous term in many fields of social science research, with a variety of definitions and usages. Kaput (1985) suggests that representation is an “undefined primitive whose meaning unfolds gradually through usage within a particular domain of inquiry” (p. 38). While in the English language the term “representation” is used in a number of different ways, making it difficult to define. The literature suggests a diversity of definitions for representation: Enyedy (2005) offers that representation is “the act of highlighting aspects of our experience and communicating them to others and ourselves” (p. 427); Goldin and Shteingold (2001) suggest that a representation is “typically a sign or a configuration of signs, characters, or objects...the important thing is that it can stand for (symbolize, depict, encode, or represent) something other than itself” (p. 3); and Lee and Karmiloff-Smith (1996b) affirm the notion that representation establishes a “stand for” relationship between referent and sign (see also Kaput, 1991, 1998). Representations are often considered from two perspectives, internal and external (Goldin, 1998; Zhang & Norman, 1994). However, this distinction may be spurious (Nemirovsky, 2009). Thus we will first consider representation in a broader sense, as constituting some measure of “stand for” or “refer to” relationship.
2.1 The “stand-for” relationship

Much of the early work on representation stems from linguistics and attempts to unpack the complex relationships between sign, signified, and signifier (de Saussure, 1959). At the most basic level, representation has been treated as a “stand for” (Goldin & Shteingold, 2001; Kaput, 1998; Lee & Karmiloff-Smith, 1996b; von Glasersfeld, 1987) or “corresponding to” (Kaput, 1998) relationship between one part of an individual’s experience and another.

While there is some general agreement that representations establish “stand-for” relationships (Kaput, 1998), the spoken, written, drawn, and even gestured entities can carry different meanings. An adult, presumably operating with a sufficient knowledge of a conventional system of representation, continually varies the meaning of representations depending on context and situation (von Glasersfeld, 1987). Thus, while there are conventional systems, there are not always conventional meanings. Some have a tendency to believe that words and images have an embodied meaning that exists as such, without interpretation. While this may be true on some level and for individuals with command over a conventional system, children engaged in the process of learning to create representational relationships are unaware of these pre-determined correspondence between signifier and signified. As von Glasersfeld (1987) states:

Because perceiving, from a constructivist point of view, is always an active making, rather than a passive receiving, the similarity of a picture and what it depicts does not reside in the two objects but in the activities of the experiencer who perceives them. Ordinary language, however, refers to objects as though they existed as such, independent of experience. Consequently, it always leads us, the language users, to attribute differences in our perceptual operating to the externalized objects as though there were properties belonging to them in an “objective” sense. Provided we remain aware of this epistemological sleight of hand, we may safely say: An iconic representation...is an artifact and a deliberate reconstruction of another experiential item; the reconstruction selects certain properties considered relevant under the circumstances. (p. 217)

Therefore, in defining representation with regard to children, it is important to consider representation as a useful referential-communicative tool (Tolchinsky-Landsmann & Karmiloff-Smith, 1992); this would constitute the process of representing, as discussed earlier. de Saussure’s arbor versus tree example (see de Saussure, 1959) also highlights a controversial dualism in representation research, which is closely linked with the discussions of the process view of representation. This dualism is the distinction between internal and external representations.

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5 For the purpose of the present argument, we group “stand-for” and “corresponds to” together, as done by Kaput. However, it is noted that upon more careful analysis of how representations are generated, these phrases can be considered different ways of viewing representational relationships. Stand-for relationships typically consist of two entities that can be interchanged to represent the same referent. There is a presumed one-to-one relationship with “stand-fors” that is evident by the replacement capability. In other words, the representation is equivalent to the referent, or the signifier is transposable with the signified. However, “corresponds to” relationships do not necessarily imply or require the same interchangeability. These relationships tend to be more analogous in nature, or they tend to point to specific aspects of the referent. There is a sense of “wholeness” to a stand-for relationship that is not required with corresponds-to relationships. Students producing external representations may generate stand-for relationships or corresponds-to relationships, depending on the context and their intent. The two terms are, thus, considered interchangeable herein, but the existence of potential differences between the representational relationships each term implies is duly noted.
2.2 Internal vs. External representations

Literature reporting traditional approaches to cognitive research has regarded representations as existing exclusively in "the mind" (Zhang & Norman, 1994). These internal representations are the subject of a large body of literature on knowledge organization in the mind, also referred to as students' internal conceptualizations (Lesh, Post, & Behr, 1987) or mental representations (Brizuela & Earnest, 2007). Donald (1991) suggests that as cultures have developed, they have relied more on external memory media, devices such as language and written notation systems that offload cognition onto the external world, subsequently freeing working memory for use in more complex tasks. Others have supported Donald by focusing on external representations (i.e., those displayed on bidimensional spaces, such as writing, numerical notation, and drawing, and those that are not, such as gesture or spoken language; Even, 1998; Martí & Pozo, 2000). According to Donald (1991), external representations of memory are mechanisms of cultural evolution and of the development of the modern human mind. Goldin (1998) defines external representations as "the shared, somewhat standardized representational systems developed through human social processes" (p. 146) supporting the belief that cultural evolution plays a critical role in the development of these systems. However, before the issue of systems of representation can be fully explored, the distinction between internal and external representations must be addressed. Goldin and Kaput (1996) state that, "the distinction that we make between external and internal systems of representation is itself simply a constructed model, developed by an observer or community of theorists to help explain an individual’s observed behavior, or the behavior of a population of individuals” (p. 407). Defining these concepts independently is consistent as a classification scheme for the purpose of research, therefore, we are not critical of Goldin (1998), Goldin and Kaput (1996), or Martí and Pozo (2000).

At the same time, one must acknowledge the relationship between internal and external forms of representation in order to avoid false implications of duality. This “phantom of dualism” (Pérez Echeverría & Scheuer, 2009) that the internal/external distinction evokes fuels the debate over whether there can exist such a separation. Pérez Echeverría and Scheuer (2009), for instance, raise the issue of whether focusing on external representations is “establishing an absolute frontier between outer and inner worlds” (p. 7). They warn against considering mental representations to be simply a collection of reproduced images, written notations, colors, sounds, or even gestures. To imagine that a child sees an image and generates a carbon copy of that image in the mind ignores the complexity of the relationship between the external and internal. Discussions whereby this literal mapping scheme is evoked have a tendency to emphasize the “phantom of dualism” because they downplay the role of sensory experiences in perceiving information, which some have warned is a dangerous trend in representations research (Nemirovsky, 2009; Pérez Echeverría & Scheuer, 2009). Nemirovsky (2009) writes,

Seeing an image is not a matter of forming a neuronal “version” of it, but of an activity that engages the motion of our eyes and bodies, the detection of edges and colors, the stereoscopy discrimination between the two eyes, and so on. Our experience of seeing something emerges from all the activities that incorporate it – incorporate in the sense of our body shaping itself to make room for the image. The bodily activity of seeing is not a
constitution of representations, in the same sense that our bodily activity of eating is not a matter of constituting representations of food. (p. 1-2).

As previously mentioned, the act of externalizing understanding involves a remapping of that conceptual object to the understanding one has. Such a process of remapping is exactly what Nemirovsky (2009) speaks toward; children do not copy what they perceive onto their mind; rather, they reconstruct connections between perception and understanding. Thus, when the focus is placed on internal versus external representations, the constant interplay between understanding and externalizations is essentially ignored. As some researchers have suggested (Nemirovsky, 2009; Pérez Echeverría & Scheuer, 2009), the focus needs to be placed on the inscriptions, notations, and symbolic expressions that children produce in particular learning environments, always keeping in mind that none of these constitute direct windows into their internal representations.

2.3 Systems of representation

Modes of expression that are conventionally used as referential-communicative tools must meet two central conditions: they must have elements (e.g., signs/symbols, inscriptions, notations) and they must have rules which govern how elements are combined. A single notation or inscription is simply a signifier with minimal meaning unless it is situated within a larger system of representation (Gardner & Wolf, 1983; Goldin, 1998; Goldin & Shteingold, 2001). Goldin (1998) cites “systems of spoken symbols, written symbol, static figural models or pictures, manipulative models and real world situations” (p. 143) as examples of systems of representation. Nemirovsky (1994) differentiates "symbol use" from "symbol systems" by maintaining that systems involve rules. Recall the role of cultural evolution in the development of representations. As conventional systems of representations used as referential-communicative tools are created, rules are simultaneously developed (either implicitly or explicitly) as means for preserving common meaning found in the relationships between signifier and the signified. Thus, the rules that govern the use of elements evolve so that the arbitrary signs of a given system may be consistently mapped to shared intended meanings.

When children learn to represent, they must learn not only the notations and inscriptions for elements within the system (e.g., letters and digits), but eventually the rules of the system as well. However, not all systems have formal rules. For example, when two people speak colloquially, there may not be an agreed upon set of rules for that system of spoken language, but they are still able to represent meaning. Lehrer and Schauble (2000a) use the term "representational model" to refer to such representations that can be part of a system but can also be unconventional and unsystematic (Brizuela, 2004). The important overarching idea to remember when discussing systems of representation is that each system contains elements and rules, and children must learn both aspects en route to becoming proficient within each system.

Brizuela (1997) shows that failure to adhere to the rules of a system does not necessarily detract from the meaning of the representation in the child's mind. Children are indeed aware of systems of representation as well as the symbols that comprise those systems, however, their

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6 A possible alternative to external representations could be “externalized representations” (Scheuer, personal communication, March 4, 2009), which acknowledges the role of the ideas and thoughts the child holds. An externalized representation is whatever observable artifact, gesture, or verbalization the child may make which is inextricably linked with whatever form of mental representation one envisions. However, we retain the term external representation herein to keep consistency with the terminology used in the literature.
conceptual dilemmas arise as they attempt to represent ideas with which they are uncomfortable. Brizuela (1997, 2004) reports on the introduction by a young child of “capital numbers,” a term used in reference to the first digit in a two-digit number. The young child, not knowing that a digit in the tens place of a numeral was called, referred to it as a “capital number.” As with the first letter of a sentence or a proper noun, which is capitalized in the English language, the student “borrowed” this term in attempts to conceptualize two-digit numbers (Brizuela, 1997, 2004). While children may tend to use a conventional oral representation of the number (i.e., the child will say “thirty six”, not “three six”), their understanding of the rules of the written system may not be fully developed. As a result, the child invents a solution to the problem: one may be using “capital numbers” to refer to the tens digit in a two-digit number. Brizuela (1997, 2004) also alluded to a larger issue, which is that “learning and constructing knowledge involve inventions – novel productions we create, using our present cognitive structures, while trying to make sense of a situation or phenomena” (p. 35). The child’s efforts to borrow from one system to make sense of another ultimately leads to a constructed understanding of the particular rules of a given system. Thus, while children are aware of the various symbols and features of different systems of representation, their invented use of these elements is one way where they can find meaning.

This is an important point to keep in mind while researching how children produce external representations. While some of the artifacts may appear meaningless from the perspective of a developed system of representation, in reality the artifact has meaning to the child, and this meaning should be explored. Therefore, researchers must value how children represent spontaneously, how they learn to represent, and how they come to learn the common rules associated with specific systems of representation, be they formal or informal.

3.0 Multiple representations

According to Pérez-Echeverría and Scheuer (2009), “The use of alternative external representations to describe a single situation assists the explication of epistemic attitude, across developmental periods, learning situations and domains of knowledge” (p. 11). Others have made a similar argument, where attempts to express knowledge across systems of representation are shown to be beneficial for conceptual understanding (Brizuela & Earnest, 2007; Lehrer & Schauble, 2002). One specific reason for the benefit of multiple representations lies in the possibility that each system of representation may highlight aspects of a problem that others do not (Kaput, 1998; Pérez-Echeverría & Scheuer, 2009; Zhang & Norman, 1994). That particular conceptual features are made more salient in certain systems, and that specific types of reasoning are supported by specific types of representations are both stances that are supported by the literature in both mathematics and science education.

A distinction is necessary prior to the review of the literature on this topic. External representations are used in this section in two different manners: expressively and interpretively (Toth, 2000), or perhaps more classically production and comprehension (Eskritt & Lee, 2007; Lee & Karmiloff-Smith, 1996a). An expressive representation or production is created by an individual in attempts to convey information to oneself or to a broader audience. These externalizations can be idiosyncratic, conventional, or a combination of both. Interpretive representations or comprehensions are given to the individual, such as with many computer

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7 Yerushalmy (1997) also calls this “manipulating the conventions” (p. 452), where students find new meaning in conventional representations to suit the needs of a particular problem.
software applications or in the case of Laura and the velocity sign (Nemirovsky, 1994). Regardless of the particular type of externalization, the general tenets of how children learn to use and appropriate these representations hold relatively consistent. Therefore, studies involving both productions and comprehensions will be included in this review.

The research in science and mathematics education has provided evidence that students can develop richer conceptual understanding and deeper knowledge of representational practices when the educational activities involve the use of multiple representations. Specifically, the variety of perspectives inherent in the many forms of representation provide for variance in which aspects of the problem are made apparent; highlighting a variety of conceptual aspects through multiple representations fosters deeper insight for children (Confrey, 1991). Highlighting conceptual elements of the same problem can guide students to uncover patterns across representations. Complex language and circumstantial issues can also be unpacked by clarifying aspects of the problem through different modes of expression (Schwartz & Yerushalmy, 1995). The use of multiple representations to increase insight has been shown to specifically help students grasp concepts like mathematical similarity (Lehrer, Strom, & Confrey, 2002), graphical notations of algebraic concepts (Schwartz & Yerushalmy, 1995), how to model plant growth (Lehrer & Schauble, 2002), and position versus time graphs (Nemirovsky, Tierney, & Wright, 1998; Thornton, 1987). As Bamberger (1991) suggests, for many individuals (students and teachers), unpacking the problem involves the exploration of many forms of that problem; that is, “different kinds of conceptualizations…can be explored by navigating across different representations of the same problem” (Brizuela & Earnest, 2007, p. 299).

Zhang and Norman (1994) introduced the concept of representational effect to address this issue of different representations linked to different conceptual aspects. They define the effect by saying that “different isomorphic representations of a common formal structure can cause dramatically different cognitive behaviors” (Zhang & Norman, 1994, p. 88; see also Kaput, 1998). In studies investigating well-known problems like tic-tac-toe (Zhang, 1997) and the Towers of Hanoi (Zhang & Norman, 1994), they were able to show that individuals showed varying ability to solve the problem based on the representation presented. Parnafes and diSessa (2004) found similar results when investigating motion through two different representations with middle school students. Their findings suggested a difference in reasoning styles based on the type of representation on which the students focused. In these examples, the students were charged with comprehending representations that were presented to them in computer software environments (Parnafes & diSessa, 2004; Zhang, 1997; Zhang & Norman, 1994). Interpreting and making-sense of representations across multiple systems has been shown to have an impact on students’ understanding of math and science ideas. However, gains in understanding have also been shown when students generate the representations across multiple systems. While some have shown the power of comprehending representations, instances of children producing representations are also powerful contexts for impacting understanding (Toth, 2000).8

Brizuela and Earnest (2007) report on elementary school students learning algebraic concepts. The students were presented with a problem and asked to first verbally articulate their view of the problem, then put on paper some representation of the problem, then generate tables, and finally discuss graphical representations. The researchers found that as the students progressively represented the problem, “the explicit and implicit qualities of notations continually refined and enhanced their understandings of the problem” (Brizuela & Earnest, 2007, p. 299).

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8 It is important to note that educational activities do not have to be exclusively interpretive or expressive. In fact, combinations of the two forms may be the most effective way for children to explore new conceptual areas.
Brenner, Mayer, Moseley, Brar, Duran, Smith, et al. (1997) showed similar results in algebra, whereby when students were introduced to new representations for problems, their frequency of use for each type increased when searching for solutions. Students appeared to show an increase in representational flexibility (Karmiloff-Smith, 1992) as they found meaning in each of the systems. Tytler and Prain’s (2007) study in the domain of science confirmed these previous findings, showing that as students constructed multiple representations of evaporation, their conceptual understanding increased. They attribute the gains to “a shift in [the students’] capacity to imagine the process whereby water can exist in air, involving the construction of a narrative of causation allied with the spatial representation” (Tytler & Prain, 2007, p. 244). The common theme running through these studies is that the exploration of concepts by students generating multiple representations results in increased conceptual understanding. However, the results of this work are contingent on a crucial principle for all educational activities, which is that educationally rich activities require posing appropriate questions such that the investigation of the concept in each of the systems yields a benefit (Friedlander & Tabach, 2001). Children can pose appropriate questions as well as teachers, with the appropriate guidance and structuring (Lehrer & Romberg, 1996). No matter who generates the problems, their appropriateness in addressing the concepts at hand must be considered. Just as the representational effect (Zhang, 1994) suggests, not all representations are best suited for all problems and thus, before children have gained representational competency, care should be taken in selecting the kinds of problems used to help teach children how to externalize knowledge.

The study we report in this paper concerns how children externalize their understanding of science concepts across multiple systems of representation, and how the process of externalizing impacts their particular understandings. The specific concepts of interest for this study are air and the particulate theory of matter.

4.0 Children’s conceptions of air and the particulate theory of matter

Modern science views air as a collection of gases described by the particulate nature of matter, stating that (1) matter is made of particles called atoms, which are too small to see with the naked eye, (2) particles are in constant motion, (3) there is empty space (a vacuum) between all particles, (4) particles are held together by strong attraction and repulsion forces, and (5) the interactions between particles determine the observable properties of matter (Johnson, 1998a). However, the Kinetic-Molecular Theory of Gases (Halliday, Resnick, & Walker, 2005) more specifically addresses the behavior of substances in the gaseous state, such as air. The theory suggests that particles in gases are widely spread (relative to liquids and solids), and they constantly collide with the walls of a container and with other particles.Attraction and repulsion forces in gases are considered to be negligible, as collisions are what dictate much of the observed behavior of gases, such as pressure or temperature. Students’ conceptions of air, air pressure, and the particulate nature of matter are well documented in the literature (Brook, Briggs, & Driver, 1984; deBerg, 1995; Driver et al., 1994; Johnson, 1998a, 1998b, 1998c; Nakhleh, Samarapungavan, & Saglam, 2005; Novick & Nussbaum, 1978, 1981; Nussbaum, 1985; Papageorgiou & Johnson, 2005; Piaget, 1930/2001; Pozo & Gómez Crespo, 2005; Séré, 1982; Tytler, 1998). Many studies investigate children’s thinking in regards to matter in the gaseous state, but air is a term and a concept that children encounter from a very young age that
must be considered independently from pure gases. Thus, both the literature on air and the literature on the particle model inform the present work, and are reviewed accordingly.

4.1 Children’s conceptions of air

Piaget (1930/2001) published some of the first work on young children’s conceptions of air, pressure, and wind. Children of young ages, Piaget found, hold strong beliefs about the relationships between air and movement. For example, clasping two hands together and generating pressure between the palms will yield a small current of air, which children of different ages conceptualize in different ways. Younger students do not believe that there is air inside a room, that is only exists outside and that the pressure generated by the hands attracts air from elsewhere (or even extracts air from inside the body). Older children, however, eventually come to realize that there is air inside the room, and that the hands simply create a small stream of air movement. Similarly, younger children tend to believe that trees generate wind, while older students come to recognize the role of air currents in moving the leaves on trees. Piaget’s (1930/2001) work paved the way for others to examine the relationship between movements and air. Seré (1982) found that young children associate a movement with the presence of air (such as with wind). However, in our study we focused on children of middle-school age (approximately 12 – 14 years of age), and most studies suggest that these students are aware of air in static conditions (Séré, 1982; Driver et al., 1994; Tytler, 1998). Focusing specifically on air as a substance (as opposed to air pressure), students of this age can conceive of air (Séré, 1982), some recognize the existence of an atmosphere (Driver et al., 1994), and many students recognize that air takes up space and its volume can be changed (deBerg, 1995; Driver, et al., 1994; Tytler, 1998). With regards to the ability of air to transmit forces, nearly all admit that air “pushes against things”, and some children specify the direction of force, claiming that air can push things forward (Driver et al., 1994). However, by age 16 less than one-quarter of students consider air as having weight (Driver et al., 1994), which suggests they are familiar with the effects of air, but less comfortable with the composition of the substance. The literature on air reports conceptions that appear plausible if we subscribe to the belief that understanding is constructed from experience. Children are comfortable with the notion of air and the effects it causes, because these are familiar situations. However, the science of air as a mixture of gases explained by the particulate nature of matter is altogether different.

4.2 Children’s conceptions of the particle nature of matter

Fensham (1994) argues that the widespread failure of children to accurately conceptualize the particulate model of matter suggests that the teaching of these concepts should be delayed. We strongly reject this notion, and the literature supports the position that students are capable of understanding aspects of a particle model at elementary and middle school ages. The literature suggests that children hold alternative ideas than what modern science purports (Brook, Briggs, & Driver, 1984; Novick & Nussbaum, 1978, 1981), however, elements of children’s thinking can be useful in the construction of normative ideas. Specifically, Brook, Briggs, and Driver (1984) found that greater than 50% of high school students use particle ideas without necessarily comprehending other essential elements of the model. Students tend to incorporate particle representations with greater frequency (Driver, et al., 1994; Nakleh &
Samarapungavan, 1999) and consistency (Pozo & Gómez Crespo, 2005) when referencing matter in the gaseous state as opposed to matter in liquid or solid forms.

Students in upper elementary and middle schools focus on bulk, macroscopic properties of air (Novick & Nussbaum, 1978; Pozo & Gómez Crespo, 2005) before being introduced to a particle model. Once the particle model has been introduced, students tend to prefer this representation (Novick & Nussbaum, 1978), but continue to hold alternative ideas about how particles are spaced and how they interact (Brook, Briggs, & Driver, 1984; Johnston, 1990; Novick & Nussbaum, 1978, 1981; Pozo & Gómez Crespo, 2005). However, despite alternative conceptions students develop a belief in a uniform particle distribution as students progress through grade levels (Novick & Nussbaum, 1981). The concept of “empty space” between particles remains challenging for children through high school and potentially into college (Driver, et al. 1994; Johnston, 1990; Novick & Nussbaum, 1981). To summarize, the literature on air and the particulate nature of matter supports a belief that students hold ideas about particles that may not be normative, but are useful in the construction of more scientifically accepted ideas. Johnson (1998a, 1998b, 1998c; Papageorgiou & Johnson, 2005) presents a way of considering children’s developmental progression with respect to a particle model that honors their attempts to make sense of the unseen, relatively abstract concept of air as particles. This work informs both the design of the study as well as the analysis of the data presented herein.

Johnson (1998a) conducted a thorough review of the literature on children’s ideas about the particulate nature of matter prior to conducting a longitudinal study on this topic. He presents (Johnson, 1998a) a developmental progression for children’s thoughts about particles based on the data collected over time. Renstrom (1988) proposed six conceptions of matter before Johnson (1998a), but admitted that it was not an empirically determined sequence. Johnson (1995) worked with students ages 11-14 over three years in an interview study (that involved drawing tasks) which yielded four classifications of pupils’ responses regarding the particle model of matter. These “models”, as Johnson (1995; 1998a) calls them, are:

1. “Model X – Continuous substance. Particle ideas have no meaning. Nothing that resembles having particles of any description is drawn.
2. Model A – Particles in the continuous substance. Particles are drawn, but the substance is said to be between the particles. The particles are additional to the substance. There can be varying degrees of ‘profile’ for the particles (weak or strong) and of association with the substance (none to close).
3. Model B – Particles are the substance, but with macroscopic character. Particles are drawn and are said to be the substance. There is nothing between the particles. Individual particles are seen as being of the same quality of the macroscopic sample – literally small bits of it.
4. Model C – Particles are the substance, properties of state are collective. Particles are drawn and are said to be the substance. The properties of a state are seen as collective properties of the particles” (Johnson, 1998a, p. 399).

The classifications of students as having one of the four prescribed models coincided with four classroom units specifically designed to teach the concept of substance. Thus, the classifications serve as benchmarks for analyzing students’ spontaneous development of models for gases and particles. Curricular interventions often assume a generalized conceptual trajectory, and Johnson’s work provides data against which students’ natural engagement with concepts can be measured. Furthermore, perhaps more important than the developmental stages is the argument that a particle model, in a variety of accuracies, aides students in the development of
understanding about substances (Papageorgiou & Johnson, 2005). The literature presented aids us in the construction of ways of analyzing students’ externalizations of air and the particulate nature of model. We will find that many of the statements in the literature hold true in this case, but that some findings oversimplify the ways in which students develop understanding of the science of air.

5.0 The study

5.1 Research questions

Considering air is a collection of gases, we must also take into consideration the role of the kinetic theory of matter or the particulate theory of matter. It is quite common that students in grades 5-8 to have exposure to the notion of molecules and possibly even particles. In representing something that is unseen, such as a gas, the use of particle representations can serve quite useful in explaining certain situations. Thus, while air is the topic on which this study focused, ideas about the particle model of matter were also explored, as this model helps to make sense of matter in the gaseous state for students at these ages.

Combining the desire to investigate the impact of multiple representations with the richness of a topic such as air lead to the development of the following research questions, which guided the design and development of this study:

• What conceptual aspects of air and a particle model of matter are children able to represent across different systems of external representation?
• How are children’s understandings of air and the particulate nature of matter impacted by representing these concepts across multiple systems?
• How are representations produced through animations both similar and different from representations produced in other systems such as oral language, drawing, and building physical artifacts?

5.2 Research setting

The study took place in an urban K-8 public school in the Greater Boston Area. The school is considered a “neighborhood” school and a majority of the students live nearby the school grounds. The school body is a very diverse population with many children coming from different cultural, economic, ethnic, and racial backgrounds. This particular school hosts numerous educational research projects and students are accustomed to having adults other than their teachers work with them on a variety of projects. Participants in this study (described in greater detail below) are from the 8th grade, and were initially engaged in SAM Animation activities in the Fall of 2007. During this time, the entire class participated in a multi-week SAM Animation lesson where the students gained experience with the use of the software and different ways of making stop-action movies. These activities purposefully ignored air, particle ideas, or other content areas used in the present research study.

5.3 Sample

Consent forms for the study were distributed to more than 100 8th grade students. Thirteen students returned consent and assent forms, and two students were chosen at random
from these twenty students as pilot cases. Interviews were carried out with each of these two students. The review of results from these two interviews led to some changes in the protocol for this study. The protocol reported in this paper reflects these changes. A sample of four students was chosen at random from the pool of participants whose parents had consented to their participation in the research study. These participants include (pseudonyms): Trish (13; 8), Fernando (14; 4), Amanda (13; 6), and Alison (14; 2).

5.4 Interview protocol

The study reported in this paper was designed to elicit multiple representations from students on the topic of air. These representations were produced after students were engaged in a science exploration\footnote{We purposefully choose the term “exploration” in place of “demonstration”. Demonstrations are generally performed such that the child (in this case) only observes the phenomena. Some research (Crouch, Fagen, Callan, & Mazur, 2004; Roth, McRobbie, Lucas, & Bouton, 1997; Shepardson, Moje, & Kennard-McClelland, 1994) suggests children will “see what they want to see” in the demonstration, and that is not the purpose of this particular study. By calling the activities “explorations” we highlight the fact that the child was given the opportunity to explore at his or her will. Whatever he or she observed was, thus, a result of his or her own actions, leading to what I believe could be a more meaningful engagement with the science topic.} for 5-10 minutes, described below. Morrison and Tversky’s (2001) "Conceptual Congruence Hypothesis" suggests that since animations depict changes over time, then the situations about which students are asked to generate animations should also include elements of motion and change over time (Schwartz, personal communication, March 15, 2007). Additionally, because air is a gas, it has compressibility properties much different than liquids or solids, and we sought to make this capacity explicit in the demonstration. Thus, a demonstration showing change over time and compressibility was chosen for this study.

Figure 1. Syringes presented to the students in the study. The single syringe (left hand side of image) was presented to the student first, followed by the linked syringes (right hand side of image).
The exploration used in this study focused on air inside large (50 cubic-centiliter) syringes. Students were first asked what they knew about air without being presented a physical prop. After a brief conversation about these initial ideas, they were presented a single syringe and asked to explore it. Each participant spent a few moments describing the syringe and his or her familiarity with the device, and then they were presented with two syringes connected at the nozzles by a short piece of rubber tubing. With this device, as the plunger of one syringe is depressed, the plunger of the other syringe extends (see Figure 1). In addition, one can simultaneously depress both syringe plungers, noticeably changing the total internal volume of the systems by compressing the air inside the device. This demonstration has been used by other researchers in investigations of children's notions of air pressure (deBerg, 1995; Séré, 1982; Tytler, 1998) and will be referred to as the "Linked-Syringe" exploration.

Participants were presented with the sealed-syringe exploration in three different 30-minute sessions, which centered on a general question: “what do you know about air based on the linked-syringes?”. Each session was a one-on-one interview utilizing the clinical interview method developed by Piaget (1929/1965) and later modified by Ginsburg (1997), among others (see also Brizuela 1997; Duckworth, 1987, 1996). The clinical interview relies on the use of tasks to elicit student thinking. Ginsburg (1997) highlights several key features of this method: (1) a protocol of questions as a starting point for the interview, (2) tasks which are specific, (3) freedom to explore lines of reasoning introduced by the interviewee, (4) encouragement of verbal justifications and explanations, and (5) the use of the interviewee’s words (among others). All three sessions were conducted using the clinical interview method wherein the participant was asked to produce representations in four different systems: oral language, drawing, stop-action movies, and physical artifacts. The first session focused first on children’s production of a drawing, the second session focused on children’s construction of an animation, and the third session focused on their construction of a physical artifact. Children’s verbalizations (oral language) in response to the question “what do you know about air based on the linked-syringes?” were kept track of during all three sessions. There were approximately 2-3 days between each session for each individual participant.

5.4.1 Drawing - Prompt: "Could you show on this piece of paper what you know about air based on the linked syringes?"

A precedent for drawing as a system of representation in which children represent their ideas about science and mathematics is well established in the literature (Acher & Arcà, 2009; diSessa, 2004; Lehrer & Schauble, 2000; Piaget & Inhelder, 1971; Sherin, 2000; Vosniadou & Brewer, 1992). In this first session, participants were initially asked what they knew about air prior to being shown the linked-syringe device. They were then shown a single syringe, followed by the linked syringes. After some moments talking about air and the devices (both the single syringe and the linked syringes), the drawing task was introduced using the above prompt. Sherin (2000) reported specifically on students’ Meta Representational Competence (MRC) with drawing, verifying that students are capable of representing spatial displacements on the referent in two-dimensional drawings. Thus, it is perfectly reasonable to assume that students are able to, at least partially, represent their knowledge about air through drawing. Students who did not spontaneously introduce a particle representation of air were prompted with a picture of a rectangular box with dots drawn inside (see Figure 3B) and were asked, “Another eighth grader showed air to me in this way, what do you think about this?”. Typically, students generated more
than one drawing in the course of the session and a new sheet of paper was introduced each time they wished to produce a new drawing.

5.4.2 Student-Generated Animations - Prompt: "Can you make an animation showing what you know about air based on the linked syringes?"

In addition to two more widely used systems of representation—drawing and oral language—this study also used two less frequently used systems of representation. One of these is animations. In Martí and Pozo’s (2000) framework, they would view this representation as a hybrid system because it can include representations from other systems as well (e.g., drawings, text). The animations used in this study were generated with a tool called SAM Animation\(^\text{10}\). SAM Animation is a piece of educational software developed by the Tufts University Center for Engineering Education and Outreach. Animations are movies comprised of a number of still images that are played in rapid succession. Early non-digital versions of animations include flip-books, where small changes in the depicted scene resulted in more fluid movements when viewed in succession for very short periods of time each (typically less than 0.1 seconds between images). In SAM Animation, a web-camera is connected to the computer that displays a live video image in one window of the software. This allows for the user to make the animation out of whatever materials they desire (e.g., drawings, manipulatives, paper cut-outs, LEGO bricks, etc.). The user "snaps" the image they want and a still picture is recorded and placed in a timeline. The user then adjusts the scene captured by the camera, and "snaps" another image. The animation is, therefore, a collection of still images taken from the camera that is focused on some scene external to the computer. The user can "play" the animation at a specific frame rate (measured in frames per second) that they prescribe. The result is a computerized movie, which can be exported as a Quicktime™ file and shared with other students, teachers, and researchers. Church, Gravel, and Rogers (2008) have previously reported on success using this software with students in high school physics courses.

Students who participated in the study had been previously introduced to the use of SAM Animation software, as described above. In the second interview session, students were asked to generate an animation based on the above prompt. To facilitate this session, the students focused on making and manipulating the physical props for the movie while the interviewer controlled the computer interface, taking action only when instructed to by the student.

5.4.3 Physical Representations with Discussion - Prompt: "Can you build me something that might show what you know about air or some aspect of air based on the linked syringes?

The second less frequently used system of representation that was used in this study is physical artifacts. Scientists regularly engage in designing experiments, building physical models, and manipulating materials that are tactile in nature. However, rarely do students have the opportunity to explore scientific concepts through the construction of physical models or representations. Thus, the process of “building an explanation” is employed in this study as an experimental (although not novel, see Penner, Giles, Lehrer, & Schauble, 1997) approach to eliciting external representations from students about science concepts – in this case, about air.

\(^{10}\) Please see http://www.samanimation.com for more information on this software.
Piaget and his colleagues in Geneva are known for their tasks (such as the seriation or classification tasks used with young children) for eliciting children’s thinking. Borrowing from that tradition and the known challenges of only relying on children’s verbalizations, physical objects and manipulatives were incorporated as the third system of representation in the final interview session. Bamberger (1991) describes the success of using a technique called "Reflective Conversation," where the researcher questions the subject while the subject manipulates tactile materials to solve a problem. Bamberger addresses the challenges of understanding children's unspoken decisions and nonverbal representations of knowledge in physical situations. Students often make decisions without being able to articulate the rationale, for example, when they try to balance a number of objects on a scale. When asked to explain how they know how to balance the scale, students will often respond, "I just knew," offering little insight into what they are thinking. Bamberger (1991) uses the Reflective Conversation to get at the "going-on" of the activity, constantly questioning the students about decisions, steps, or processes to gain another perspective on how the child is representing their knowledge. Researchers often show children demonstrations (not explorations, as this study did) and ask for their explanations, but rarely ask children to construct physical objects that demonstrate their explanation. Based on Bamberger’s Reflective Conversation, the final session in the interview protocol asked participants to build something that would demonstrate some aspect of air based on the syringe exploration.

The materials included for this task were carefully selected to scaffold student’s explorations with the goal of developing a final artifact that children felt represented their understanding. By selecting materials that were easy to manipulate and aesthetically pleasing, children held a better chance of producing artifacts with which they felt comfortable. Instead of giving students a limitless supply of materials, they were first asked to write a list of what materials they might use, and then they perused the provided materials to begin constructing the artifact11.

5.5 Data collection

All of the interviews were videotaped, audio recorded, and transcribed to ensure that the verbalizations of each session were captured. Each of the drawings was collected and scanned, the animations were collected and remain in digital format (Quicktime™ movie files), and the physical artifacts were photographed. Each participant, then, has a portfolio of oral representations, drawings, animations, and physical artifacts comprising the record for each case.

5.6 Analysis

The analysis of the data gathered from the four students in each of the three interview sessions was analyzed in three steps: (1) development of interview overviews; (2) development of coding scheme; and (3) development of code groupings.

5.6.1 Interview overviews

11 Generating a detailed list of materials proved rather difficult for all of the students, but the process of thinking about what materials they might consider led them to hone in on some conceptual aspects of the problem they wished to represent.
As mentioned before, this work is grounded in the qualitative clinical interview tradition where prolonged, multifaceted exposure with each participant allows for a thorough, in-depth analysis of the role of external representation in the development of science ideas. To accurately (and fairly) present the work of each student, overviews of all three interview sessions were developed with examples from each student’s verbalizations and productions. The intent of these overviews was to: (a) characterize each student’s model for air and the particulate nature of matter, (b) describe the evolution of scientific ideas throughout each of the sessions, and (c) identify the role that external representations played in the construction of science understanding. While these accounts are lengthy and detailed, they provided valuable context for considering more specific issues addressed later in the results. In keeping with the qualitative tradition, validity and trustworthiness of the data hinge on the reader understanding how each student constructed understanding and representations for air.

5.6.2 Coding scheme

Based on the transcripts of each interview session, conceptual codes representing ideas about air, gases, and the particulate theory of matter were developed for categorizing both the verbalizations and productions from each episode. From the literature, a set of relevant codes were selected based on what other researchers have reported. The codes and data were discussed with numerous researchers, and a final set of codes was created that combined similar ideas and excluded codes that were not relevant to the current dataset. The data were coded based on utterances (small phrases or sentences) which pertained to each of the codes in the scheme. For some more elaborate verbalizations, multiple codes were applied depending on the ideas addressed in the utterance.

5.6.3 Code groupings

Reviews of the data initially confirmed our hypothesis that certain conceptual aspects of air were represented more frequently in certain systems of representation. In an attempt to investigate this hypothesis, the codes were divided into two groupings: (1) those pertaining to the material aspects of air and the particulate nature of matter, and (2) the codes that related to process aspects of the context as well as air and particles. This analysis provided for a comparison between the type of representation (oral language, drawing, animation, or physical construction) and the frequency of ideas represented by each student and by the collective group of participants.

6.0 Results

The overall sample size was small for this interview study, however, an in-depth description of one student’s trajectory through the sessions highlights many of the aspects of external representation that we are concerned with herein. While Trish’s story is illustrative of the sample, similar to other single case studies (Confrey, 1991; Nemirovsky, 1994; Piaget, 1936/1977), we are not suggesting these results are generalizable in their current form.

6.1 Trish
Trish is a middle-class, white female student who is relatively quiet and is considered to “do well in school” by her teachers. The transcripts reveal her lack of confidence in many of her verbalizations (as is indicated by frequent “I don’t know” statements). However, her ideas about air and the particulate nature of matter became increasingly complex as the sessions proceeded. The story of Trish’s trajectory through three interview sessions highlights the interplay between developing an understanding of material substances in service of trying to make sense of processes, such as those represented in the linked syringe exploration.

6.1.1 Interview and drawing: Focusing on air as a substance

In the first session, Trish was presented with the question, “What is air?” She offered that air is made of gases and that it exists everywhere, but she struggled to articulate specific aspects of air as a substance, “cause, you can’t see it…water is different because it’s like, actually there.” Trish’s efforts to describe air as a substance characterized her verbalizations and productions for the first session.

The single syringe provided Trish with a context for beginning to speak about air as a substance. She comfortably explained that there was air in the syringe and that depressing the plunger pushed the air out of the syringe. When presented with the linked syringes, Trish’s verbalizations about air began to take shape.

B: So, what do you think will happen when I push one of these [the syringe plungers] down?
T: This one [points to the opposite plunger] will go up.

[Trish depresses one plunger and the opposite plunger extends.]

B: Very good. So what do you think will happen if you pull this one up?
T: This might, this will come down.
B: OK…
T: Yeah…cause there’s air in here [syringe with plunger extended], and then when you push it, it goes and pushes that one.
B: What do you know about air from playing with this? Can you tell me?
T: Let’s see, it takes up space. At least like this, cause when you push it [syringe plunger that is extended] up then it [air] has to go over there cause, yeah…

Trish’s efforts to predict the results of the syringe exploration and her subsequent explanations helped her consider conceptual aspects of air as a substance. While she was asked about two scenarios (pushing one syringe plunger down to extend the other, and extending one plunger to depress the opposite), her attention remained focused on describing air and how it moved as a quantity. Trish realized that the air inside the linked syringes was a consistent quantity (i.e., no air could be added or removed), and she used this information to describe what she saw. She argued that air moving from one syringe to the other needs a place to go, so the opposite syringe plunger extends. This explanation treats air in this context to be a continuous substance, rather than a more normative representation of air as a discrete collection of particles. Trish’s observations were explained using this continuous model of air as a substance, however, her statements were quite naïve at this point in the session.

While the focus of Trish’s attention during the interview portion of the session (before drawing was introduced) was on air as a substance, she questioned what would happen if she
tried pressing both syringes at the same time. In exploring her question, she was exploring the process of compression, and she recognized that “the air compresses to fit in a smaller space.” However, her belief that air is a continuous substance appeared insufficient for generating an articulated verbal explanation for this process.

B: And how do you know that it’s a smaller space?
T: Because you’re pushing both of them down, so it’s making it shorter.
B: Gotcha, so this area is becoming smaller on both ends?
T: Yeah.
B: And the space in the tube, that’s not changing, or is it?
T: [Shakes head no.]
B: So when you say…what’s happening, do you think, to the air that allows it to get smaller? You said compression, but what do you think that really means?
T: Um…
B: How could you describe it?
T: I guess, I don’t know. It’s like…um…like squishing, I guess. Like, I don’t know. It’s weird because it’s like, I don’t know, like you can’t see it except for it’s getting smaller, so it’s kind of weird.

While Trish was comfortable talking about the process of compression, her explanation of what compression means was limited. Perhaps she holds a model for air (presumably a continuous representation) that does not provide her with the resources necessary to explain such a process; a continuous representation of air does not easily provide for a way of talking about compression. It was not until she began to draw her ideas that the continuous representation evolved into something more useful.

Trish was asked to put something on paper to explain what she had observed, and she drew linked syringes with scribbled lines representing air inside the syringes (see Figure 2). Trish made explicit the stipulation that “you need a contained space” by writing these words alongside her drawing, further evidence of her interest in the contained quantity of air in the system.

Figure 2. Trish’s first drawing depicting the linked syringe case.
Figure 3. (a) Trish’s second drawing of air in a closed container; (b) Drawing representation of particles of air in a closed container.
Trish was asked to represent air in a container and she produced a drawing with continuous lines representing air (Figure 3A). Trish’s thinking was probed when the first author of this paper presented her with a particle representation of air and asked, “Another 8th grader drew air this way, what do you think about that?” (Figure 3B). Trish paused and then began to contemplate the particle (Figure 3B) version. She replied, “I guess, because, they could…but I think it would fill the whole thing, well, I don’t know. Cause these [dots on the page] could be like air molecules, or something, I don’t know.” Trish initially questioned the particle representation (i.e., Figure 3B) but began incorporating it into her productions. When asked to recreate her drawing (see Figure 4), the revision included dots on paper as representations of air. Trish went as far as to show a different spacing of dots to represent compression. She offered, “If you pushed this, both of the ends down like this, then there

![Figure 4. Trish’s recreated linked-syringe drawing including dots representing “air molecules”.

would be like more of them…So, they would like squish together, so there would be a lot more in one space.” Considering air to be a collection of particles as opposed to one continuous substance appears to have proved useful for Trish.

Regarding air as made of molecules encouraged Trish to think of a variety of ways in which these particles could be spaced depending on whether they were being “squished.” With that said, simply representing air as particles versus a continuous substance does not provide answers to other problems with the syringe explorations, such as why the plungers can only be compressed to a certain point. When explaining this scenario Trish stated, “Because they’re…like, entirely squished together, so there would be a lot more in one space.” It is unclear what substance air might become when the gas particles are “entirely squished together.” Regardless, Trish was developing her understanding of air, and the process of representing particles on paper appears to have helped her gain clarity in her explanation of compression. Even if her verbalizations were non-normative (i.e., “entirely squished together”), the consideration she gave to particles and their interaction shows some change in her thinking about air as a substance. Trish’s development of a richer representation of the material substance aspects of air is further evidenced by her continued exploration of compression in the syringes.

B: When we let go of this [air in syringes being compressed by pressing both plungers], why do you think it moves back up?
T: Cause they’re spread out?
B: So they want to be spread out?
T: Yeah…
B: Why do you think that is?
T:…
B: Got any ideas?
T: Um…because…I don’t know. Um…I don’t know. I guess that, like, the air that we
breath and stuff, or like the air that’s everywhere is not compressed, but like, I don’t
know, it’s just…I don’t know, it wants to be spread out.

Her commitment to the term “spread out” indicated two points: (1) she was developing an
understanding and a representation for particle interaction, and (2) her understanding of the
material substance properties of air provides her with resources to contemplate process aspects
on a deeper level. While Trish offered no explanation for why particles “want to be spread out,”
the utterance demonstrates that her attention has shifted to considering not only air as particles
but how particles may interact with each other. Trish’s attention to material substance aspects of
air and her initial representations of a particle model are clear trends in this first interview and
drawing session. She talked about process topics, but this only led to further engagement with
material substance ideas. In the animation session, we see Trish begin to build on the particle
representations she constructed in this first session as means for thinking about processes.

6.1.2 Animation: Making sense of process

When Trish was asked to make a stop-action movie about air based on the linked
syringes, she immediately attended to the problem of representing “air molecules” and her
understanding of compression, perhaps picking up from her last set of concerns from the
previous Drawing session. She settled on small pieces of paper as representations of air
molecules moving inside an outline of linked syringes (see Figures 5 and 6). The process of
generating the comparison between the compression states prompted her to say, “It’s like how it

Figure 5. Screen-shot of Trish’s animation showing paper dots as air molecules “spread out” in the linked-syringes.

Figure 6. Screen-shot of Trish’s animation showing air molecules “getting squished together”.

would be if you didn’t touch it, and they’re, like, spread out.” When both plungers are pressed,
she commented that the air molecules are “getting squished together” (see Figure 6). Both of
these statements were carried over from the drawing session, where she appeared to have honed
her representations of air as particles, prompted initially by the interviewer’s intervention. Poised
with an understanding of how particles might interact and how differences in air particle spacing can represent different levels of pressure, Trish constructed a representation of force transfer through air that was remarkably sophisticated.

While generating the animation, Trish took great care to move all the air particles (represented as paper dots) together along the device. That is, when representing the case where one plunger is depressed and the other extends, she moved all the air particles in succession along the image. Implicit in this representation is a potential mechanism for transferring forces in a closed system – another process idea. In Trish’s animation, molecules move toward those closest to them, which in turn move toward the next proximal particles, and so forth to transfer the force. Such a mechanism relates to the Newtonian model involving attraction and repulsion forces. A more current view is that a force applied to a gas in such a situation results in collisions between particles being propagated in the direction of the force (because the gas is in a contained space). Regardless of whether Trish’s representation was normative, generating this animation positioned Trish to consider the interaction between particles, including force transfer. For example, when asked why one feels resistance on the plungers if they are both being depressed, she argued that there was “too much air” in the system. From her point of view, one could depress the plungers further, if there was less air in the system to be compressed. Implicit in her statement is a belief in a limit regarding how much air can be compressed. She commented earlier about compression decreasing the space between molecules, thus, she seems to be contemplating particle interactions. Rather than a clear articulation of pressure and force, however, her animation and explanation illustrate a movement toward thinking in greater detail about the interaction between particles in different scenarios.

There was a shift in conceptual focus from the first session to the second session. The oral and drawing session yielded a larger number of utterances concerning the material substance nature of air. That session evolved into utterances and productions of particles and particle spacing, but mostly remaining in what we could consider to be a material substance domain. However, in the animation session, Trish was able to reproduce the particle representations she generated in the first session to begin addressing issues of process. Her animation showed how particles under pressure interact in the syringe system. It also included a representation of a force transfer mechanism between the particles of air. Thus, for Trish, the animation session appeared better suited for her to explore process ideas, while material substance ideas were more frequent during the oral language and drawing session. This is a recurrent theme that will be addressed in detail below. Spending time contemplating what air consists of, how those elements interact, and how to represent those interactions led Trish to begin questioning and further verbalizing her assumptions about air during the physical construction task.

6.1.2 Physical construction: Particles and processes

Confronted with the request of building something to help describe properties of air, Trish opted to re-represent the linked syringe device.

T: So we have to figure out a way to show the air molecules, I don't know what we could use.
B: What did we use in the animation?
T: Paper...dots. But they have to be able to, like, move around and stuff. And, it has be something that you can, like, pick up.
B: What do you mean, you can pick up?
T: Like, something, like, not like a paper.
B: Right, ok...so...
T: Alright...I guess we could use paper for the air molecules, kind of. But then we have to be able to show this thingy [the syringe].
B: So, you were saying you think you could use paper, like little paper dots, like you did in the animation to show air...
T: [Nods head yes.]
B: What other kinds of stuff would help us show air?
T: Um...but we're going to have to be able to show, like, all the stuff that we did, like, when you push down on both sides of it, or when you push on one side, so they have to be able to move around. But, like, we can't, like, they would just all, like, fall, I don't know, like, it wouldn't work.
B: What do you mean they would all like fall?
T: Like, if you were to make one of these [syringe] and then put paper in it as the dots, they wouldn't, like, do what you wanted, because they're not air.
B: Ok...
T: So...
B: But you think you'd want to try and make something that would show the air molecules and how they interact or how they move through the system?12
T: How they move through the system, and, like, like, become more, like, dense when they're squished together.

Trish was primarily concerned with finding a physical representation of an air molecule. The above episode illustrates the challenge she had in finding a physical material or element that would mimic the qualities of an air molecule, as she understood them. At this point, we do not know exactly how Trish would represent an air molecule. Perhaps her struggles to find the right material are indicative of a lack of clarity in her individual, idiosyncratic representations of air. Trish’s discomfort demonstrates the challenge of externally representing an unseen. But, that challenge is likely confounded by working within a hybrid system such as physical construction, which is an unfamiliar way of externalizing understanding for most students. She likely has little experience representing an unseen entity, such as a gas particle, using raw construction materials. Trish’s question about how to capture the idea of an air particle in a physical instantiation is part of the challenge of externalizing an unseen idea in an unfamiliar way.

The fact that it is challenging does not mean we should shy away from these situations; on the contrary, the complexity underlying the situation could bring about important conceptual developments. This process could result in the individual engaging in the problem and content at a deeper level, as Trish, for instance, must confront her conceptions of air particles, regardless of whether she is able to articulate these assumptions. Her statement, “They wouldn't, like, do what you wanted, because they're not air,” provides the researcher with a window into her present representation for air molecules. Some aspect of how small pieces of paper behave is counter to her understanding of air molecules, and the process of trying to externalize her understanding in this physical system allows us a glimpse at the assumptions inherent in her understanding.

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12 In the first interview session, Trish had been introduced to the syringes as a “system”, and was thus familiar with the term in reference to the device during this exchange.
Eventually, Trish decided on small, stainless steel ball bearings as a representation for air, but immediately expressed her discomfort and reservations about representing the particles in this manner. She said, “They wouldn’t, like, move the same as air molecules, I don’t think…they’re like things, they’re not like…” at which point she struggled to verbalize her hesitations about the ball bearings. Earlier, Trish had described air molecules as being able to “float,” thus her reservation about the metal ball bearings could stem from a desire to represent the same behavior. She seemed genuinely uneasy because she continued to describe air as “something,” but a different sort of something than the ball bearings. Trish’s continued challenges in verbalizing this difference may suggest that oral language is not the most comfortable system for her to externalize these ideas. We can postulate that engaging in the exercise of finding a physical, observable representation of air molecules may help Trish develop her understanding of an air molecule; time spent exploring possible representations for a molecule in a physical system could help her to construct an oral representation of her understanding. While further evidence is necessary to confirm or deny this hypothesis, it is clear that Trish was focused on material substance aspects of air during the first segment of the construction session. However, once a representation for air was chosen, her focus began to shift toward representing “how they move through the system.”

Trish built her device (see Figure 7), and it was a single syringe representation containing ball bearings meant to represent air molecules. With the device built, Trish began contemplating some of the processes that she explored in the earlier sessions, namely how she achieved compression with the two syringes. The ball bearings in her device tended to line up in an ordered configuration, which again made Trish uncomfortable. The ordered, compact nature of ball bearings in a line was in conflict with her belief that “when you push down on both sides it needs space to, like, get squished together.” No visible space between the air molecule representations was evidence that contradicted her understanding of compression. Instead of altering her explanation of how air was compressed in the linked syringes, she chose to point out the limitations of the model she had built while verbalizing her understanding.

Figure 7. Trish’s physical construction of air in the linked syringes.
B: What do you think they [air particles] look like in here [points to the tube]? Do you have any idea what kind of arrangement they would be in? Do you think they'd all be in a line, would they all be ever, or would it be kind of random, what do you think?
T: I think it would be kind of random.
B: How come?
T: Because, um, I don't know if they're all, like, the same shape or whatever. They're just like...cause they're definitely not like these balls.
B: They're not like the, well, you already said that the balls are heavier, but what else? How else are they different?
T: Um...these, like, go down to one side and air molecules, like, float.
B: Ah, ok. So the air molecules, what's another way you could say that they float? Like another way to describe that.
T: They're...um, in the air, I guess. Like, I mean, like, they don't, like... they... like...gravity doesn't change them. It doesn't make them, like, go down or whatever.
B: Ok, it doesn’t make them go down. Let's think about it this way, if I've got air and this is one space in here [pointing to the linked syringe device], does air fill the whole space or is it only in part of the space?
T: Yeah, it fills the whole space.
B: Ok.
T: But, spread out.

This exchange illustrates how the process of explaining how a representation is not like the situation in question turned out to be an interesting and valuable aspect of constructing physical artifacts. Highlighting the aspects of a system that are at odds with one’s ideas not only compels the student to question those assumptions but also provides the researcher with an interesting window into what aspects of air are most interesting or important for the student. Trish appears to hold an intriguing belief in a relationship between gravity and air molecules. Likely, she believes that gravity pulls things toward the earth, and air molecules somehow defy the force of gravity. While these are non-normative ideas, the process of representing understanding in this physical, hybrid system elicits aspects of thought that may otherwise remain unnoticed. In this session, Trish began contemplating the problem of representing the material substance aspects of air. As she constructed the device and used it to explain her understanding, her attention shifted toward the processes inherent in the linked syringe problem. In the prior sessions, she appeared to focus on either material substance ideas or process ideas, but rarely were they simultaneously considered. In this third and final session, she begins to blend her representations for air as a substance with her understanding of the processes air goes through. This progression is intriguing and revealing and will be discussed in more detail later on.

6.1.3 Trish: Summary

Trish’s experience throughout three interview sessions provide evidence for the interplay between systems of representation and conceptual aspects of air. She began with an emphasis on the material substance aspects of air during the oral language and drawing session. Initially representing air as a continuous substance, Trish slowly transitioned into a particulate representation once it was introduced to her in drawing form. Her attempts to make sense of how the system worked required an understanding of the material substance. Trish’s continuous
model gradually transitioned into a particle model (due, in part, we assume, to the introduction of this idea by the interviewer), which led to her subsequent contemplation of the processes involved in the linked syringe exploration. Whether the limitations of a continuous model were evident to her is unclear, but regardless, representing air as particles proved more fruitful for Trish.

The particle model carried over into the animation session, where she used particles to represent the processes of force transfer and compression. While she focused her verbalizations on material substance aspects of air in the first session (oral language and drawing), her focus shifted to process ideas during the animation session. One could argue that she spent the first session constructing a representation for air as a substance, and in the animation session she began to consider process ideas involving particles of air. Both sessions prepared her for the physical construction task, where she further related the ideas and representations she produced in the first two sessions. Trish appeared to strike a balance between material substance and process ideas in the construction session. It was during this interview that she also pushed the limits of her understanding of the linked syringe case. Her trajectory suggests a measure of order effect in how the sessions were deployed; however, the connections between systems of representation and conceptual aspects of air remain intriguing.

6.2 Quantitative trends

Children have been shown to harbor different conceptions about material substance and process aspects of natural phenomena (Chi, 1992; Slotta, Chi, & Joram, 1995). Thinking about what something is as compared with how something changes requires different cognitive resources for students. This categorization can be applied to air, as there are decidedly different aspects of air as a material and the processes air undergoes. It is reasonable to suspect that a relationship exists between systems of representation and conceptual aspects of phenomena, such as with air. The analysis presented here attempts to differentiate between the systems of representation employed in this study and the characteristics of air that students tended to highlight within and with each system.

The data were coded as described, and two categories of codes were generated based on Chi’s (1992; Slotta, Chi, & Joram, 1995) work on material substance and process aspects of science phenomena13. Based on these categories, the data were organized according to conceptual aspects (i.e., material substance or process), and Chi-squared tests were performed to analyze the observed outcomes versus expected outcomes. In this case, the null hypothesis was that no difference in the frequency of material substance as compared with process ideas would exist across or within the systems of representation employed. The interviews were divided into four sessions, whereby the interview (before the child was allowed to draw), drawing, animation, and physical construction are all treated as four separate sessions. This distinction was created to compare what ideas students attended to while attempting to externalize their understanding using different systems of representation.

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13 It should be noted that using Chi’s (1992) categorization of material substance and process ideas does not presuppose an adherence to her theory of ontological categories and conceptual change. This issue is discussed in further detail in the Discussion section.
Table 1. Utterance frequencies within session/type of representation.

<table>
<thead>
<tr>
<th></th>
<th>Interview</th>
<th>Drawing</th>
<th>Animation</th>
<th>Physical</th>
</tr>
</thead>
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<tr>
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<td>84</td>
<td>73</td>
<td>78</td>
</tr>
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<td>8.627**</td>
<td>0.641</td>
<td>2.348</td>
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</tbody>
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* p < 0.05, ** p < 0.01, *** p < 0.001

Table 1 reports the total frequencies of material substance and process ideas uttered by all students for each of the four session categories listed. The total number of material-substance utterances in the interview and drawing session was significantly higher than expected when compared to process ideas. While not significant, the number of process ideas uttered in the animation sessions was higher than the number of material-substance ideas. Lastly, material-substance ideas appeared to dominate process ideas during the physical representation session; as was shown by Trish’s focused attention on selecting an appropriate representation for an air molecule – in her case, the metal ball bearing.

Table 2. Utterances across sessions, grouped by conceptual aspects of air (i.e., material substance and process).

<table>
<thead>
<tr>
<th></th>
<th>Interview</th>
<th>Drawing</th>
<th>Animation</th>
<th>Physical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material - Substance</td>
<td>57</td>
<td>84</td>
<td>73</td>
<td>78</td>
</tr>
<tr>
<td>% of total utterances</td>
<td>19.52</td>
<td>28.77</td>
<td>25.00</td>
<td>26.71</td>
</tr>
<tr>
<td>Chi Square</td>
<td>2.401</td>
<td>1.135</td>
<td>0</td>
<td>0.235</td>
</tr>
<tr>
<td>Process</td>
<td>27</td>
<td>50</td>
<td>83</td>
<td>60</td>
</tr>
<tr>
<td>% of total utterances</td>
<td>12.27</td>
<td>22.73</td>
<td>37.73</td>
<td>27.27</td>
</tr>
<tr>
<td>Chi Square</td>
<td>12.959**</td>
<td>0.413</td>
<td>12.959**</td>
<td>0.413</td>
</tr>
</tbody>
</table>

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 2 compares the frequencies of material substance and process ideas across sessions. In other words, this analysis attempts to highlight the patterns in terms of where material substance and process ideas are most likely to show up. As Table 2 shows, material substance ideas were significantly underrepresented in the interview sessions, whereas process ideas were significantly overrepresented in the animation sessions. That is, material substance ideas appear more likely in oral language settings than expected, and process utterances appear more frequently in animation settings than expected. With Trish, the animation provided her with an opportunity to explore the ways in which particles interacted in the system, thus leading her to externalize a number of process ideas during the session.

In addition to utterances, the students’ productions were also coded for differences between material substance and process aspects of air. Productions were coded using a similar set of codes as the utterances, with some additional codes used to categorize elements of the productions. Table 3 shows the frequencies (i.e., the total number of material substance and process ideas represented by all students in each category of production) of material-substance and process codes present in the productions organized by type of production (oral language was
not included in this analysis, as the other analyses focused on utterances). The null hypothesis was that material substance and process ideas would be equally probable in each of the productions. The data suggest that material substance ideas are more frequently represented in drawings than expected, and less frequently present in physical constructions than expected. Similarly, while not significant, process ideas are represented in animations more than was expected. Overall, the results suggest a relationship between conceptual aspects of air and systems of representation. These results are further expanded upon in discussion section.

Table 3. Productions across sessions, grouped by conceptual aspects of air (i.e., material substance and process).

<table>
<thead>
<tr>
<th>Material - Substance</th>
<th>Drawing</th>
<th>Animation</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of total occurrences</td>
<td>54.79</td>
<td>27.40</td>
<td>17.81</td>
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<tr>
<td>Chi Square</td>
<td>27.749***</td>
<td>2.093</td>
<td>14.41***</td>
</tr>
<tr>
<td>Process</td>
<td>10</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>% of total occurrences</td>
<td>28.57</td>
<td>40.00</td>
<td>31.43</td>
</tr>
<tr>
<td>Chi Square</td>
<td>1.3429</td>
<td>2.696</td>
<td>0.210</td>
</tr>
</tbody>
</table>

* p < 0.05, ** p < 0.01, *** p < 0.001

7.0 Discussion

For the students participating in this study, the process of constructing representations across multiple systems helped them to explore different conceptual aspects of air and, thus, develop a more sophisticated understanding. The context for the investigations was specifically chosen such that students would observe changes over time. With the linked syringes, students were able to explore multiple processes including compression of a gaseous quantity and force transfer through a gas. Additionally, the adoption of a particle model of matter provided the students with resources for contemplating the processes they observed on a deeper level than the more continuous models many of them held initially. Thus, the exploration (i.e., the linked syringes) must be considered in this study, as inherent in that system were opportunities for students to explore both material substance and process aspects of air.

The data suggest a relationship between specific systems of representation and certain conceptual aspects of air. The students demonstrated a tendency to focus their utterances and productions on material substance aspects of air in the interview and drawing tasks. Drawing is a relatively static system of representation, whereby showing motion and processes can be considered more challenging than in other, more dynamic systems of representation. Conversely, drawing offers opportunities for careful analysis of moments in time, including the material substance qualities of air at a given moment. Students’ attempts to represent their understanding of air in oral language and in drawing resulted in a tendency to focus on “what air is”. With Trish, for example, we saw her struggle to articulate an explanation of air during the interview session and the beginning of the drawing session. Trish successfully described what she observed, and her drawing listed some key aspects of the linked syringe system (e.g., the requirement of a “contained space”); however, her representations (both oral and in drawing) did not offer detailed explanations of why the system behaved as it did. The introduction of a particle
model (by the interviewer) initiated a change in Trish’s ways of representing the situation. However, these new particle utterances and the inclusion of “dots” in her drawings remained focused on making sense of air as a substance (i.e., a collection of particles). Interestingly, as Trish contended with the problem of representing air, the development of particle ideas lead her to naturally begin considering the processes demonstrated by the linked syringes.

The quantitative analysis confirms the finding that there may, in fact, be a relationship between the systems of representation and the conceptual aspects of air externalized by the participants. Table 1 demonstrates the frequency distributions wherein material substance ideas were much more prevalent than expected in the interview and drawing sessions. Table 2 shows that across all systems, process ideas are more likely to be represented during the animation session than expected. This trend is enlightened by a deeper analysis of the affordances of the animation environment. With stop-action movies, students engage in a process of showing change over time. A movie has an inherent temporal dependency whereby each frame is reliant on the previous frame, as well as the upcoming. When a student is creating a specific frame (e.g., by moving dots of paper along a syringe drawing, such as the case with Trish), he or she must be mindful of the previous frame, as well as the next frame. In other words, generating one instance of the movie involves knowing where you came from and where you are going. This implicit temporal dimension of animation can be considered as an affordance that allows for natural exploration of change over time (i.e., processes). Perhaps students tend to focus on process ideas while engaged in generating an animation because the system itself is predisposed to representing processes. The data from the productions is less clear, but still suggests an increase in the number of process ideas represented in the animations as compared with drawings or physical constructions. For Trish, the animation was a way to demonstrate her understanding of compression as well as a representation for force transfer. As the literature suggests, both of these concepts are notoriously challenging for students, yet Trish demonstrated capacity for grappling with these process ideas. While we take care not to conjecture too strongly about the production data, it warrants future investigation into aspects of animation that may make it a powerful medium for exploring change over time.

The physical construction task may be the most abstract system utilized in the study, as building a conceptual model is a formidable challenge. Those with mastery of the conceptual domain may find difficulty in selecting appropriate materials to represent the concept; however, this challenge may be beneficial for students. Constructing a physical representation of air requires selecting an element to “stand for” the substance, while also representing some aspect of the context and how it changes over time. When constructing the stand-for relationship, the student is faced with having to confront any assumptions or presuppositions he or she holds about the substance. With Trish, she continually remarked how the ball bearings she selected to stand-for air were not like air molecules. Making explicit the differences between the representation and the referent may have helped Trish develop a richer understanding of air as particles; engaging in a process of externalizing an idea and re-linking those external representations to her model for air likely improved her understanding. In terms of systems of representation, perhaps physical constructions yield a more equivalent distribution of process and material substance utterances because efforts to represent the process are inextricably linked with choosing a suitable representation for the substance. Trish wanted to show her understanding of how the air molecules moved through the system, which for her was dependent on describing how the metal ball bearings were not acting as she believed air molecules would.
The particular nuances of which conceptual aspects are more likely represented in which system require further investigation, particularly with a larger sample. However, one summative finding appears relatively clear: students tend to represent different ideas in different systems of representation and, thus, should be given opportunities to do so in science classes. Asking children to externalize their understanding in multiple ways not only allows them to explore aspects of their own thinking, but also provides the researcher or teacher with a multidimensional view of what the student believes and how they represent their ideas. Students engaged with a single system of representation may lack the opportunities to challenge their thinking and may be deprived of the chance to refine their models for how the world works. Therefore, we promote the use of multiple forms of representation in the exploration of science concepts.

In addition to the relationships between conceptual aspects of air and systems of representation, there are additional issues related to the literature on children learning science that deserve attention. First, as others have suggested (diSessa et al., 1991; Enyedy, 2005), students engaged in a process of progressive symbolization develop increasingly sophisticated understandings of science and mathematics concepts. Externalizing and re-representing ideas in a cyclical nature, as the students in this study were asked to do, aides the development of conceptual understanding as well as the development of the abilities to externalize ideas (Kaput, 1991). As we saw with Trish, the incorporation of particle ideas from the time they were introduced through the remaining sessions shows how that particular idea or model proved useful for her. Concurrently, Trish’s representations of particles and how they interact gained complexity in each re-representation (or representational redescriptions as Karmiloff-Smith (1990) might suggest). We offer this as evidence of the power of iterative representation in science learning. We also recognize that Karmiloff-Smith’s (1990) and Enyedy’s (2005) constructs are rooted in how children develop an understanding of conventional representations such as mathematical notation and written language. Even though representations of air were not based on elements from conventional systems (e.g., written number), students in this study underwent a process of creating representations that were considered conceptual objects in much the same way as conventional elements are described. With Trish, a discussion of how a ball bearing is not like an air molecule presumes that the ball bearing has effectively become part of the concept of an air molecule, as its limitations could not be considered until its status as “representation” was accepted. While not conventional, representations as objects allow the students to evaluate their externalizations en route to generating a more refined and sophisticated re-representation. We believe the interplay between the process of generating representations and the evaluation of these products as conceptual objects suggests that there is no strict dichotomy either developmentally or conceptually between process and object. In other words, the process of representing is also a process of objectifying – occurring simultaneously in some cases, such as with Trish and the discussions of how a ball bearing is not an air molecule.

Similarly, these data suggest that the distinction between process and material substance aspects of science concepts (suggested by Chi, 1992) may be erroneous. While Chi (1992) is correct in identifying the differences between process aspects and material substance aspects of a concept such as air, we propose that the process of representing those aspects across multiple systems allows students to concurrently develop notions of how processes and material substances ideas are related. The context of externalizing understanding through the production of multiple representations allows students to explore how material substance and process ideas can be cooperative, as opposed to in conflict to each other. Much of Chi’s work (see Chi 1992;
Slotta, Chi, & Joram, 1995) illustrates the difficulties students have with switching between material substance and process ideas; however, perhaps the lens of multiple representations may help the students make these transitions. Again, more work is needed to provide more sufficient evidence of this process/material substance issue, but we feel this issue deserves greater attention. Ultimately, in the case of Trish, the introduction of a particle model of air provided her with a representation of the material substance that aided her investigations of processes. In turn, her efforts to conceptualize the processes inherent in the linked-syringe case forced her to reassess her notions of material substance. Therefore, this approach to unpacking a concept such as air and the particle nature of matter may be powerful in inducing shifts in foci and changes in conceptual understanding.

8.0 Future work

The data presented here suggest a deep, complex relationship between external representations and various aspects of science concepts, such as air. However, continued investigation into this relationship could increase its impact on the field of science education. The process versus material substance distinction used in the quantitative analysis revealed compelling trends across each system of representation. However, as the excerpts from Trish illustrate, both the utterances and productions possess rich and complicated conceptions of air and the particle nature of matter that could be probed in greater detail. Improved coding schemes and methods for categorizing not only the ideas but the ways in which these ideas are represented in each of the sessions is needed. An increased sample size and potentially the introduction of additional content topics (such as heat or light) would strengthen these findings as well.

An important implication of this work for education could lie in the introduction of a particle model to middle school-aged students. As Papageorgiou and Johnson (2005) suggest, a particle model of matter is useful in helping students contemplate issues of material substance. We feel these data also suggest that children of this age are capable of thinking about air as particles and are able to use this notion in the exploration of process ideas. For Trish, the introduction of air as dots on paper led her to consider a particle model, which proved useful in her contemplation of more advanced ideas such as compression and force transfer. Furthermore, the opportunity to represent a concept in multiple ways helped Trish transition between different conceptual aspects of science as well as to undergo changes in her conceptual understanding. Therefore, the introduction of a particle model coupled with the process of progressive symbolization across multiple systems of representation proved a successful strategy and could be thought of as a potential classroom intervention.

References


Brizuela, B. M. (2001). Children's ideas about the written number system: Harvard University Graduate School of Education.


