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Developmental Differences in Relational Reasoning Among Primary and Secondary School Students

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Relational reasoning, the ability to discern meaningful patterns within a stream of information, is considered a critical capacity for students. However, little is known about how this ability is demonstrated by children of different ages in the context of discourse with a more knowledgeable other. Thus, this study sought to investigate the ways in which 4 forms of relational reasoning (i.e., analogy, anomaly, antinomy, and antitheses) manifested in semistructured conversations between a researcher and child about the form and function of more or less familiar objects. Participants were a nationally representative cross-sectional sample of 61 New Zealand primary and secondary students, divided into 3 grade groups: early (Kindergarten through second), middle (fourth through eighth), and late (tenth through eleventh). Results indicated that children as young as 5 years old were capable of using all 4 forms of relational reasoning in discourse. Furthermore, analysis revealed a curvilinear trajectory in the observed versus expected frequencies of relational reasoning among the groups. Finally, in terms of the individual forms of relational reasoning, analogies and anomalies occupied a smaller proportion of relational talk when children were older, whereas antinomies and antitheses occupied a greater proportion. Implications for research and practice are forwarded.

Keywords: relational reasoning, development, analogy, anomaly, antithesis

Relational reasoning, the ability to discern meaningful patterns within any informational stream (Alexander & the Disciplined Reading and Learning Research Laboratory, 2012), has been cited as a critical capacity for learning in both formal and informal settings (Chuang & She, 2013; Gentner, 1989; Son, Smith, & Goldstone, 2011). Indeed, this construct has enjoyed a rich history within the educational psychology canon. William James (1890) originally characterized human attention as being "trained by both association and disassociation" (p. 487), or, the ability to draw a variety of relations among objects and ideas that we encounter. Later, Charles Spearman (1927), in his magnum opus, *The Abilities of Man*, proposed three laws that he believed shape cognition, one of which was a fundamental ability to construct relations among any two or more objects, ideas, or situations. Of such a capacity he remarked: "In ordinary life, [the relations of likeness and opposition] appear to be the most universal of all cognitive tools" (p. 173).

From young children's taxonomic categorizations (Gelman, 1979) to experts' chunking skills (Chase & Simon, 1973), relational reasoning has proven to be a pervasive cognitive process in any situation requiring the integration of concepts, objects, or ideas. The act of relational reasoning is considered an exemplar of higher-order thinking to the extent that it entails the effortful, purposeful, and goal-directed engagement with such concepts, objects, or ideas. Alexander and colleagues (2011) suggest that during periods of higher-order thinking learners move beyond the routine and superficial toward a more reflective, evaluative, and strategic processing. Moreover, when engaged in higher-order thinking, learners transform their knowledge as they analyze, coordinate, and resolve information from multiple sources. Both reflective and transformational thinking are considered attributes of relational reasoning (Alexander & the Disciplined Reading and Learning Research Laboratory, 2012). Furthermore, relational reasoning has been described as a metastrategy (Alexander & Baggetta, 2014), which by definition is not only broadly applicable to a range of domains or problem-solving tasks (i.e., domain general; Pressley, Goodchild, Fleet, Zajchowski, & Evans, 1989) but also encompasses some degree of executive or oversight function (Dumas, Alexander, Baker, Jablansky, & Dunbar, 2014). In the current study, we examine manifestations of relational reasoning as it iterates in the task domain of technological literacy.

With the understanding that relational reasoning is a core capacity for individuals, researchers have conducted a variety of

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investigations that have empirically linked this cognitive ability to academic success in reading (Farrington-Flint & Wood, 2007), mathematics (Alexander, White, & Daugherty, 1997), and science (Chuang & She, 2013; Haglund, Jeppsson, & Andersson, 2012), as well as to problem solving in naturalistic settings (Bearman, Ball, & Ormerod, 2002; Christensen & Schunn, 2007; Dunbar, 1995; Paletz, Schunn, & Kim, 2013). Such results have demonstrated that relational reasoning is present in individuals as young as 3 years old and beyond the age of 80 (Cattell, 1971, 1987; Crone et al., 2009; Fischer, Norberg, & Lundman, 2008; Gentner & Rattermann, 1991; Kuhn, Garcia-Mila, Zohar, & Andersen, 1995). Although it is clear that relational reasoning occurs throughout the life span, there are few, if any, studies that address the qualitative and quantitative differences in relational reasoning among individuals in early childhood (e.g., 4 to 5 years old) through late adolescence (e.g., 17 to 18 years old).

Development of Relational Reasoning

Exploring the emergence of relational reasoning, researchers have revealed that relational integration (i.e., the ability to map one relation onto another) occurs as young as 5 years old and steadily increases with age (Andrews & Halford, 1998; Richland, Morrison, & Holyoak, 2006). This ability may be a product of relational knowledge and a subsequent ability to focus on structural (i.e., deep), as opposed to featural, relations (Gentner, 1988; Rattermann & Gentner, 1998). Indeed, forays into neuroscience have suggested that while children (i.e., under the age of 12) and adults (i.e., individuals 18 and older) use the same brain structures to solve analogical reasoning problems, only adults are able to successfully integrate several relations simultaneously (Crone et al., 2009; Krawczyk, 2012).

In addition to an enhanced ability to integrate increasingly complex relations, researchers have noted the pivotal role of field-specific knowledge for relational reasoning. In fact, certain researchers maintain that the development of analogical reasoning is not predominantly a product of age, but rather of deepening knowledge of a field (Gentner & Rattermann, 1991; Goswami, 1992, 1996; Goswami & Brown, 1990; Halford, 1992; Halford, Wilson, & Phillips, 1998; Rattermann & Gentner, 1998); knowledge that enables children to better represent a concept in their minds and consider how objects or ideas might be related. As such, the capacity to reason relationally may be more or less prevalent depending on the objects or domains involved and the corresponding familiarity that the objects or domains represent to the respondent. In effect, when children are more familiar with a task or an object about which they reflect, their reasoning may be more logical or naturalistic in nature, whereas a lack of familiarity may increase the likelihood of noncausal explanations (Berzonsky, 1971). Hence, prior experiences and the knowledge arising from those experiences may support individuals' ability to posit viable relations between and among otherwise independent or unassociated objects or ideas (Dunbar & Klahr, 1989; Klahr & Dunbar, 1988).

However, the development of relational reasoning may not be solely dependent on factors related to the individual. In fact, this capacity may rely as much on the affordances of the external environment as it does on the cognitive capacity to draw such relations (Mercer, Dawes, Wegerif, & Sams, 2004). For instance, collaborative interactions with more learned individuals who can scaffold complex ideas or model appropriated reasoning strategies have been shown to aid children in developing higher-order problem-solving skills (Rojas-Drummond, Mercer, & Dabrowski, 2001). However, as children's general cognitive skills, task or object familiarity, and field-specific knowledge increase, the degree of scaffolding needed to elicit relational reasoning may well correspondingly decrease (Chi, Feltovich, & Glaser, 1981; Gentner & Rattermann, 1991).

Thus, there appears to be a myriad of potential variables at play in the manifestation of relational reasoning across the life span. Moreover, it seems likely that there is some degree of interaction among such variables as age, field-specific knowledge, and task or object familiarity in the display of such reasoning. In addition, it seems logical that the presence of scaffolded discussion with a more knowledgeable "other" could prompt increasingly complex relational reasoning processes than might be expected otherwise, especially for those who are younger and less experienced at the task at hand.

Issues Within the Relational Reasoning Literature

In spite of a surge of research pertaining to relational reasoning, the literature demonstrates several shortcomings. Methodologically, studies concerned with gauging relational reasoning ability in children and youth have primarily used nonverbal measures such as the Raven's Progressive Matrices (e.g., Eslinger et al., 2009; Raven, 1938), scene and pictures analogies (e.g., Krawczyk, 2012; Richland et al., 2006), or children's toys (e.g., Andrews & Halford, 1998). These studies overlook the fact that relational reasoning need not be confined to formal assessments, but can be witnessed in conversations or other forms of verbal exchanges engaged in shared problem solving (Dumas et al., 2014).

Perhaps more importantly, relational reasoning has principally been operationalized as analogical in nature; that is, dealing with the higher-order relation of similarity (Alexander & the Disciplined Reading and Learning Research Laboratory, 2012). Indeed, the ability to draw relations of similarity is considered among the most fundamental and essential of capacities for organizing thought (Hofstadter, 2001). However, relational reasoning appears in fact be a broader construct that encompasses various forms of reasoning. Therefore, solely investigating instances of analogical reasoning may prevent researchers from discovering critical information about the interplay of a variety of relational processes. Moreover, if relational reasoning is a multidimensional construct, then the overall developmental portraits of relational reasoning, as well as the individual trajectories of the specific forms of reasoning, may be more nuanced than our current understanding of relational reasoning would suggest. For instance, it is possible that younger children will be limited or inconsistent in their demonstration of relational reasoning, whereas older children's or youth's relational reasoning repertoires may be noticeably more extensive or better honed. Furthermore, the number of instances of relational reasoning forms verbalized by individuals may increase or decrease depending on their familiarity with the object or task at hand or on the extent of scaffolded support they require or receive.

Forms of Relational Reasoning

As noted, Alexander and the Disciplined Reading and Learning Research Laboratory (2012) suggest that there are at least three other forms of relational reasoning than the often-studied form of AGs—anomalies (AMs), antinomies (ANs), and antitheses (ATs). What distinguishes these forms is the nature of the relation drawn from one situation to another (Dumas, Alexander, & Grossnickle, 2013). Specifically, an anomaly (AM) is defined as an outlier within a set or deviation from an expected pattern or rule (Dumas et al., 2014; Klahr & Dunbar, 1988). In the context of an evaluation of artifact form and function, a child presented with a football for the first time might note that it is a ball, but that it is not like other sports balls because of its shape. In this way, the child has discerned the higher-level relation of discrepancy, noting that while most balls are spherical, this ball deviates from the typical pattern by being a kind of ellipse. Like analogical reasoning, anomalous reasoning appears to evolve as individuals develop more knowledge of and experience with a particular field (Koslowski, 1996; Schauble, Glaser, Raghavan, & Reiner, 1991), although children as young as 4 have been known to reason anomalously (Schulz, Goodman, Tenenbaum, & Jenkins, 2008).

Antinomous reasoning, which deals with incompatibility and often involves categorization on the basis of mutual exclusivity (Dumas et al., 2013; Slotta & Chi, 2006), has also been found to develop as individuals augment their knowledge of a field (Schneider & Hardy, 2013). A child might recognize that an ornamental glass orb, like a ball, is round. Despite that shared attribute, however, the glass orb cannot be placed in the category of "ball" because it cannot be bounced, thrown, or otherwise played with. Thus, antinomies represent classifications that are constructed by reasoning about what an object or idea is *not* or *cannot be*. Researchers have demonstrated that while both younger and older children are able to make taxonomic categorizations, older children are significantly better able to focus on the structural aspects of categories (Taverna & Peralta, 2013).

Finally, antithetical reasoning involves relations of direct opposition (Chinn & Anderson, 1998; Kuhn & Udell, 2007). Such reasoning often arises as individuals evaluate an object's design and purpose. An individual can contrast a beach ball with a golf ball along the continua of size and hardness. In so doing, the person might determine via antithetical reasoning that these two balls sit at opposite ends of these two continua; the beach ball is very large but very soft, whereas the golf ball is very small but very hard. Although there are studies that examine the development of such reasoning in very young children, they are limited in their generalizability. These studies have traditionally used antithetical reasoning as a means to study other phenomena such as executive functions (e.g., Baker, Friedman, & Leslie, 2010) or magnitude understanding (Whitacre et al., 2012). In addition, they have done so using inhibition tasks or magnitude comparisons. This lack of methodological consistency, coupled with a more peripheral focus on relational reasoning, makes it difficult to hypothesize how antithetical reasoning in discourse would manifest in children of different ages. Therefore, the general developmental trajectory of antithetical reasoning is largely unknown.

Although these four forms of relational reasoning can be distinguished by the key association derived from the informational stream (e.g., discrepancy vs. exclusion), they nonetheless have foundational cognitive processes in common. Drawing on Sternberg's (1977) componential framework for analogical reasoning, we contend that AMs, ANs, and ATs likewise involve the processes of encoding, inferring, mapping, and applying. Specifically, *encoding* and *inferring* pertain to the identification of specific attributes of the objects of reasoning and the formulation of associations between those given objects, respectively. As such, the outcomes from encoding and inferring can be characterized as lower-order in nature. By comparison, mapping requires the discernment of the overarching relation between and among problem objects, guided by the outcomes of encoding and inferring. In this way, it is result of the mapping that largely determines the class of relational reasoning represented. Within component theory, *applying* is the step of using the outcomes of all preceding cognitive processes to resolve the problem at hand.

Task Domain

Given that relational reasoning involves the detection of patterns among objects and ideas (e.g., Alexander & the Disciplined Reading and Learning Research Laboratory, 2012; Dunbar & Klahr, 2012; Lawson, 2010), it was hypothesized that the analysis of technological objects, especially novel ones, would afford the opportunity for children and youth to reason relationally. Thus, the task domain chosen for this investigation was technological literacy, and more particularly students' analyses of more or less familiar technological objects as to their potential form and function. Prior research has indeed demonstrated that children and adults reason differently when they are making judgments about the form and function of novel artifacts versus those that are familiar (Defeyter, Hearing, & German, 2009). However, no research, to our knowledge, has examined how such reasoning manifests for both primary and secondary school students. Furthermore, of the research that has been conducted, it is unclear whether age, field knowledge, task or object familiarity, or some other variable might account for the observed differences between children and adults. Thus, we hypothesized that presenting students in primary and secondary grades with more or less familiar objects and prompting them to engage in reflection as to the form and function of said objects would serve as fertile ground for the study of relational reasoning. Moreover, we reasoned that the verbal exchanges between participants and a more knowledgeable other, whose role it was to scaffold the object analysis to some extent, would afford the opportunity to explore certain questions about the development of relational reasoning in its varied forms (e.g., AG or AN).

Data Source

In addition to recognizing the need for students to develop reasoning abilities required to grapple with an increasingly technologically oriented society, the New Zealand Ministry of Education (2007) supports a strong technology curriculum for the purpose of producing informed citizens who can critically and creatively engage with their world. In this sense, the Ministry has moved toward a more sociocultural view of technology; that is, a shift from the mere possession of technology skills toward a more holistic understanding of functionality, aesthetics, and fitness for purpose (Compton & Harwood, 2005).

In the present study, we had the opportunity to examine reasoning processes through semistructured conversations between students and researchers about the technological features of objects, conducted as part of a national research project, *Technological Literacy: Implications for Teaching and Learning* (TL:IMPS; Compton, Compton, & Patterson, 2011). This project endeavored to investigate students' technological literacy skills and to find ways of furthering those skills in the three distinct categories of technological literacy outlined by the New Zealand Curriculum: technological practice, technological knowledge, and nature of technology (Ministry of Education, 2007). The aim was not only that students achieve greater competence in each, but also that they develop a complex and nuanced understanding of technology in a more holistic sense. We had reason to believe that the same approach to uncovering gradations in students' technological literacy skills, through conversations with students about the features of objects with which they were more and less familiar, used by the TL:IMPS project, would also elicit occasions of relational reasoning.

Broadly, the New Zealand Ministry of Education conceptualizes technology as an intervening force in the world that is influenced by (and reciprocally influences) historical, social, and cultural events (Ministry of Education, 2007). A technological artifact, therefore, is conceived as not only an object with its own design and purpose, but also as an instantiation of its sociocultural milieu. The objects in this study, while not technological in the sense of being electronic or high-tech, were chosen very specifically to elicit differing levels of understanding about two components of technological literacy, fit for purpose and good design. *Fit for purpose* refers to the degree of match between an object's physical and functional qualities, whereas *good design* pertains to the extent to which the object accommodates its intended user and purpose and demonstrates good aesthetics (Compton, Compton, & Patterson, 2012; Compton & Harwood, 2005). An understanding of these concepts is considered essential for achieving technological literacy (Ministry of Education, 2007).

We sought to approach such a study by analyzing the discourse between students and a more knowledgeable other (i.e., researcher) as part of a nationwide cross-sectional study of New Zealand students, aged 5 to 17, as they reasoned about familiar and unfamiliar technological objects. We reasoned that a content analysis of the real-time interactions between researcher and student would demonstrate good ecological validity, because conversations with others may evoke the occasions of reasoning that might otherwise remain internal and unvoiced. Therefore, semistructured conversations would allow us to see how relational reasoning manifests in discussions unfolding in the moment. Moreover, these real-time conversations would give us the opportunity to see how relational reasoning arises naturally, rather than in a context in which students are explicitly directed to demonstrate such reasoning.

Broadly, our purpose was to explore the instances and nature of relational reasoning among primary- and secondary-school students and their association with students' problem solving. It is important to note that the main objective of the conversations was not to elicit relational reasoning, but rather to prompt students' evaluations of the form and function of two objects, varying in familiarity. While research has been conducted on particular forms of relational reasoning in isolation (e.g., Baker, Friedman, & Leslie, 2010; Gardner, 1995; Leech, Mareschal, & Cooper, 2007; Trickett, Trafton, & Schunn, 2009), no studies of which we are aware have allowed researchers to construct portraits of relational reasoning in its varied forms in children of such a wide age range (Dumas et al., 2013); nor have these existing studies used discourse patterns as the means of investigation.

Specifically, three research questions framed this investigation:

1. Which forms of relational reasoning emerge in the discourse of students as they express their understanding of the form and function of more familiar or less familiar technological objects?

Given the success of empirical endeavors to demonstrate young children's ability to generate metaphors and draw analogic comparisons among objects and ideas (Gelman, 1979; White & Alexander, 1986), we would expect to see evidence of analogical reasoning in even our youngest subjects. Furthermore, we postulated that as knowledge and communication skills increase (i.e., with age), children and youth would generate more and more complex analogic relations.

As with AGs, the presence of anomalous reasoning has been observed at a variety of ages, from children as young as 9 months old (Kosugi, Ishida, Murai, & Fujita, 2009; Schulz, Goodman, Tenenbaum, & Jenkins, 2008) to adults considered experts in their respective fields (Trickett et al., 2009). However, the methodologies used to investigate such reasoning have varied widely depending on the population of interest. For instance, while some have used head-turning preference paradigms or neuroscientific measures to draw conclusions about the capacity for anomalous reasoning (Chen et al., 2007; Sanford, Leuthold, Bohan, & Sanford, 2011), others have relied on subjects' verbalizations of AMs (Trickett et al., 2009). This discrepancy in methods renders generalizations about anomalous reasoning nearly impossible. More important, because the methodology used in the present study more closely resembles those used with experts (i.e., discourse analysis), but does so with a population much younger than is typical for such studies, it is unclear whether we will see anomalous reasoning emerge in young children.

Again, research has demonstrated the presence of taxonomic categorizations, or antinomous reasoning, in younger and older individuals (Gelman, 1979; Mosenthal, 1988; Opfer & Gelman, 2011). In spite of such findings, there appears to be conflicting evidence about the domains in which such reasoning can be effectively used by individuals of different ages. Some researchers, for example, have found evidence that infants can make categorical distinctions between animate and inanimate objects (Opfer & Gelman, 2011). However, university students were found to have trouble making ontological distinctions about physics concepts (Slotta & Chi, 2006). Such research highlights the potential importance of experience with and knowledge of a domain for fostering antinomous reasoning. Thus, we would predict that when children have developed an understanding of technological form and function, as well as the expectations of them within their technological literacy curriculum, they should demonstrate instances of antinimous reasoning.

Antithetical reasoning has similarly been found in individuals of various ages. However, because most of the empirical research on this form of reasoning has examined learning outcomes through the use of refutation texts in university students (e.g., Diakidoy, Mouskounti, & Ioannides, 2011; Heit & Nicholson, 2010) and inhibitory control in preschoolers (e.g., Baker et al., 2010), it was unclear whether semistructured conversations on the form and function of technological artifacts would elicit such reasoning.

Nonetheless, the extent to which these objects bring conflicting ideas or experiences to the fore of children's minds may be aligned with the manifestation of antithetical reasoning.

2. How do the relative proportions of verbalizations of each form of relational reasoning change across years of schooling as well as for designated reasoning cohorts?

Theoretically, if cognitive maturity (i.e., age) and field-specific knowledge are key factors in all four types of reasoning, then children should demonstrate more instances and varied types of reasoning as they age and as they gain more experience with different objects and task domains. However, the Model of Domain Learning (MDL; Alexander, 1997, 2003) provides competing theoretical explanations of how relational reasoning might unfold over time. The model proposes three stages of development—acclimation, competence, and proficiency—each characterized by a particular configuration of knowledge, interest, and strategic processing. According to this model, relational reasoning may become evident as primary- and secondary-school students develop more knowledge about the design and function of technological objects (Compton, Compton, & Patterson, 2011), become more invested in this problem-solving activity, or hone and expand their repertoire of general problem-solving strategies.

In light of such theoretical possibilities, we would predict that the occurrence of relational reasoning among kindergarteners, second, and fourth graders (i.e., the youngest students) would be minimal. By contrast, we would expect that students in the middle grades (sixth and eighth graders) would manifest the attributes of those in late acclimation, in that the occasions of relational reasoning would be higher. Finally, for those in secondary school, particularly eleventh graders, we would hypothesize that there would be evidence of competence in their problem-solving behavior, marked by more frequent instances of relational reasoning. However, given the exploratory nature of the study and the controversy within the literature as to the cognitive capabilities of young children (Gentner, 1977; White & Alexander, 1986), we would hesitate to assume that an increasing competence in relational reasoning would apply equally to all of the forms under study, or even whether particular forms might only appear in later acclimation or competence.

3. How does the degree of support offered by researcher to student change across grade levels, in association with the age of the child and level of familiarity with the object?

Taking a sociocultural approach, we would predict a greater proportion of researcher-to-student talk when the need for support from a more knowledgeable other, potentially indicative of scaffolding, is highest. Thus, when students possess little knowledge of the task domain and are unfamiliar with the objects presented to them, they should talk proportionally less relative to the prompts and support offered them by the researcher. In keeping with Vygotsky's (1978) zone of proximal development, the less knowledgeable or less experienced student may evidence varied forms and instances of relational reasoning to the extent that this reasoning is supported by the researcher within the context of the semistructured conversations (Vygotsky, 1978). In contrast, when students possess greater knowledge of technological form and function, and have had more experience with the objects, we would expect their talk to be proportionally greater than that of the researcher. The influence of such support on primary and secondary school students, in tandem with students' deepening knowledge and experiences, however, remains an empirical question not yet well addressed by the extant literature.

Method

Participants

Participants were 61 students (30 male; 49.18%) in New Zealand. Students ranged from 5 to 17 years of age (Grades K to 11). For the current in-depth investigation of relational reasoning, a random block design was employed to select a representative sample from an existing database consisting of 1,428 New Zealand students who engaged in semistructured conversations about technological objects. Specifically, after organizing the data by ethnicity, gender, and school socioeconomic level, students were drawn from approximately every other grade from kindergarten through eleventh to allow for insights into developmental differences among students of a wide age range. The resulting breakdown of sample size per grade was as follows: kindergarten ($n = 10$; 16%), second ($n = 7$; 11.5%), fourth ($n = 8$; 13%), sixth ($n = 10$; 16%), eighth ($n = 10$; 16%), tenth ($n = 10$; 16%), and eleventh grades ($n = 6$; 9.8%). In some cases, there were fewer than 10 subjects per grade; this was done to include an equal number of males and females in each group. Because of concern regarding gender differences in technological domains (e.g., U.S. Department of Education, Institute of Educational Sciences [IES], 2015), we felt it important to maintain a balanced proportion of males and females, thus eliminating gender as an explanatory factor.

Students came from 19 different schools in both urban and rural New Zealand and a range of socioeconomic backgrounds. Specifically, students came from schools ranging in decile ranking from 1 (i.e., the lowest socioeconomic status) to 10 (i.e., the highest socioeconomic status). The specific breakdown of participants by deciles was as follows: 1 ($n = 3$; 4.9%); 4 ($n = 9$; 14.8%); 5 ($n = 4$; 6.6%); 6 ($n = 9$; 14.8%); 7 ($n = 12$; 19.7%); 8 ($n = 7$; 11.5%); 9 ($n = 8$;13.1%); and, 10 ($n = 9$; 14.8%). Ethnically, the sample was 70.5% ($n = 43$) Pakeha (Whites of European descent), 23.0% Maori ($n = 14$), 3.3% ($n = 2$) Asian, and 1.6% Pasifika ($n = 1$). An additional 1.6% ($n = 1$) self-identified as "Other." These percentages are generally representative of the New Zealand population for individuals between the ages of 5 and 17 years old (Statistics New Zealand Tatauranga Aotearoa, 2015).

Semistructured Conversations

Focal objects. Two objects were utilized in the semistructured conversations, one considered familiar to students (i.e., juice box), and one judged to be relatively unfamiliar (i.e., vegetable cutter; Table 1). It had been reasoned that most students would have experience with a juice box, regardless of their age. The vegetable cutter used as the unfamiliar object was unique in that it was designed as a clear box with a set of wheels and several blades inside of it that would move when the wheels were rolled along a surface. In this way, the vegetable cutter was manufactured with the purpose of having its form obscure its function, making it difficult for students to immediately detect its use. To establish that this particular object was unfamiliar to most students, we coded whether students could identify what the object was at the outset of the semistructured conversations. Specifically, we coded whether a student knew that the object was (1) intended for food and (2) used to cut. In keeping with predictions, 87% ($n = 53$) of students were not able to identify one or both of these object features, suggesting that the object was indeed unfamiliar.

Table 1
Semi-Structured Conversation Objects and Questions

Familiar object	Semistructured conversation questions
Juice box 	Why has this product been developed? What materials have been used to make the packaging/the bottle? Why do you think these materials were selected? How do you think this is made? How does the juice get inside the packaging? Do you think this is a good form of packaging for a juice product? Why/why not? Do you think this is a good product? Why/why not? Have you heard the term fit for purpose before? *If student has come up with a useable definition of fit for purpose . . .* Do you think this a product is "fit for purpose"? Why/why not?
Unfamiliar object	
Vegetable cutter 	What do you think this is? Why do you think this? (prompt around materials, shape, parts etc) How do you think it might work? *If student has come up with a firmish idea of what it is and its use . . .* Who do you think it was designed for? Why do you think it was designed? Do you think it is a good design? What does something have to have for you to call it a "good design"?

Note. See the online article for the color version of this table.

Procedure. The researcher met individually with participants in an empty room or in the back of their classroom and informed them that their conversations would be audio recorded. As participants interacted with the focal objects set out before them, they were asked questions intended to solicit information on their impressions of fit for purpose and quality of design of each object. In conducting the larger study, the TL:IMPs research team decided to present the familiar object first, followed by the unfamiliar. Because this was a novel task, it was reasoned that presenting the participants, who included primary students, with the familiar object first would help orient them to the task. Similar to adaptive testing, which aims to meet students at their own ability level and reduce the potential anxiety and subsequent decrement in performance associated with problems that are perceived as too difficult (Eggen & Verschoor, 2006), we endeavored to eliminate such negative effects by having students initially interact with an more commonplace object.

For the familiar object, students were first asked why it had been developed, followed by questions about the materials of which it was composed and why those particular materials had been chosen. Then, they were asked to reason about how the juice got inside the package and to evaluate whether it was a good form of packaging for a juice product. Finally, they were asked to indicate whether the juice box was "fit for purpose," provided that they had demonstrated an understanding of the term.

Students were then presented with the unfamiliar object and asked for an initial impression of what it was, how it worked, and why they thought so. They were told that they could pick up the object and play with it if they wished. If the student was able to come up with a coherent idea of what the object was and what it was used for, they were then asked who it had been designed for, why it had been designed, and whether or not it could be considered a "good design." If not, then the conversation ended.

The set of questions that served as the core of the semistructured conversations are displayed in Table 1. Conversations ranged in length from 2 to 13.3 min, with an average time of 5.64 min (*SD* = 1.91). Although researchers ensured that the content of these questions was addressed, they were flexible with the order in which they asked questions. For instance, if a student discussed aspects of the object's fitness for purpose at outset of the conversation, the researcher would ask for more information at that moment rather than waiting until the end to ask whether it was fit for its purpose. Thus, although conversations looked qualitatively different from student to student, each student eventually addressed all questions outlined in the conversation protocol. In this way, these semistructured conversations shared several aspects in common with dynamic assessment (Tzuriel, 2000).

The dynamic assessment approach emphasizes the inability of static tests (e.g., multiple-choice tests) to accurately capture children's cognitive abilities, advocating instead for an interactional approach in which a more knowledgeable other functions as a mediator between a child (i.e., test-taker) and a task (Feuerstein, Rand, & Hoffman, 1979). Considering the dynamic assessment approach in tandem with the sociocultural view of technology supported by the New Zealand Ministry of Education, semistructured conversations between researcher and student were viewed as an appropriate way to query students about their understandings of technological form and function and, thus, unearth instances of relational reasoning.

Coding. The discourse produced was first divided into conversation units, which roughly constitute complete thoughts expressed by an individual and are often indicated by a disruption in discourse or pause in speech (Trickett & Trafton, 2007). Because the students' reasoning was the focus of the study, the researchers' speech was omitted from the analysis on relational reasoning, and only students' conversation units were coded. However, both the researchers' and students' conversation units were counted for a comparison of the relative contributions of each to the conversation as a whole. Two coders independently examined 20% of conversations (i.e., 13) and coded both for speech units and relational reasoning units. There was a high level of interrater agreement among the coders both for speech units (92.6%) and for relational units coded (91.3%; κ = .88).

Nature and form of conversation units. A total of 2,441 conversation units were coded across 61 conversations. If the student identified a pattern or drew a relation between two objects, people, or ideas, the unit was coded as a relational reasoning unit, and further divided into its corresponding type: AG, AM, AN, or AT.

An AG was coded if the relation drawn by the student was one of relational similarity. For instance, one fourth-grade student described the unfamiliar object in the following way: "It opens and shuts like a clip." This was coded as an AG because the student was able to identify a pattern of functioning in the object and relate it to an object he knew operated similarly.

An AM was coded when a relation of difference or nonconformity was drawn. In one example, an eighth-grade student examining the vegetable cutter remarked that it was probably designed for "people who cook at home, cause there are probably commercial ones and they probably do it differently." In this way, the student's explanation of what stood out about this vegetable cutter, or was anomalous about it, helped him to reason about who it might have been designed for.

An was coded when a relation of mutual exclusivity or incompatibility was expressed. A sixth-grade student discussing the materials used to make the juice box said, "It's probably not cardboard, but kind of plastic." This was coded AN because it described what the material was by describing what it was not.

Finally, AT was coded when a relation of contrast or opposition was described. One sixth-grade student reasoned, for example, that for something to be good design, "It has to be fast and quite easy to use instead of quite hard." By pitting the idea of utility against that of difficulty, the student verbalized an antithetical relation.

A total of 228 units were identified as relational in nature. The remaining units were then coded as either task-related or off-task (Table 2). A task-related (TR) unit was one in which the student was engaged in answering the researcher's question but did not demonstrate any type of relational reasoning. One student said of the vegetable cutter, "Maybe it could be used for some type of meat if you're trying to dice it up or mince like that." While there was no relational reasoning evident, the student was engaged in the task of identifying the object's function, thereby classifying it as task-related. A total of 1,781 TR units were coded.

The remaining 432 units, considered off-task, were then classified as either clarifying (CL) or unelaborated (UN). A CL unit was coded when the student had a question for the researcher, needed more prompting before answering a question, or had simply misheard the question. In one instance, the researcher asked the child, "Have you heard of the term fit for purpose?" to which the child responded, "Pardon?" Because the child misheard the researcher and was not directly engaged in the task of answering a question about the object, the statement was coded CL. Finally, a UN unit was coded when the student offered a "yes," "no," or "I don't know" answer to a question without explanation. For instance, when asked, "Do you think it's a good design?" one student replied, "Yeah." These types of units were coded as a distinct category because, while they were indeed task-related, they could only serve as a cursory indicator of students' reasoning. A total of 69 CL and 363 UN units were coded.

It is important there were no instances of off-task remarks that contained an instance of relational reasoning. In fact, all conversation units could be coded into one of the specified categories. Furthermore, all instances of relational reasoning were determined to fit into one the relational categories, and no forms of relational reasoning beyond AG, AM, AN, and AT were identified. A specific segment of a conversation is included in Figure 1 and is coded accordingly. A slash (/) denotes a conversation unit and the

Table 2
Frequency of Nonrelational Conversation Units by Grade

Type of conversation unit	Total	Groups, *f* (%)		
		Early	Middle	Late
All units	2,441	856 (35.1)	858 (35.1)	727 (29.8)
Clarifying	69	28 (40.6)	26 (37.7)	15 (21.7)
Unelaborated	363	153 (42.2)	110 (30.3)	100 (27.5)
Task-related	1,781	592 (33.2)	628 (35.3)	561 (31.5)

Researcher: Okay, do you think it's a good design?

TR

Child: Um… It's a pretty cool design./ I mean, yeah, it's cool, cause we've got a science similar

AG TR

to this where it's like you take a container, you take off the lid, yeah./ Yeah it is a cool design./

Figure 1. Example coding segment. TR = task related; AG = analogy.

codes above the speech indicate the type of unit coded. In this example, the student draws an analogical relational (AG) as he discusses why the unfamiliar object, the vegetable cutter, might be considered a good design.

Word counts. To assess the degree of support offered by the researcher (i.e., the more knowledgeable other), the number of words used both by researcher and student in each conversation were counted. Word counts were conducted for both of the objects (i.e., familiar and unfamiliar) individually as well as the conversation in totality. This method has been established in the quality talk literature as a means of gauging both who has control over the conversation, as well as the extent of scaffolding by the more knowledgeable other (Murphy, Wilkinson, Soter, Hennessey, & Alexander, 2009). Especially in conversations geared toward providing students with opportunities for reasoning and argumentation, longer talking turns by the more knowledgeable partner tend to denote attempts to model or scaffold complex concepts (Chinn et al., 2001; Soter & Rudge, 2008).

Results and Discussion

Forms of Relational Reasoning Used in Analyzing Technological Objects

Relational reasoning by form. Our first research question pertained to the types of relational reasoning that would emerge in semistructured conversations between primary and secondary school students and researchers about more or less familiar technological objects. As summarized in Table 3, we found instances of all four forms of relational reasoning for students even as young as kindergarten. Of the 228 total relational reasoning units found, 61.4% (n = 140) were analogical in nature, 13.2% (n = 30) anomalous, 13.6% (n = 31) antinomous, and 11.8% (n = 27) antithetical.

To confirm that these observed proportions were significantly different, a χ^2 test of goodness-of-fit was utilized, $\chi^2(3) = 161.30$, $p < .001$. Because of the significance of this test, we were able to infer that, although the each of the four forms were observed in our sample, they were not present in equivalent proportions. Specifically, AGs dominated the discourse, with each of the other three forms appearing in relatively smaller proportions.

Table 3
Frequency of Relational Reasoning Units by Group

Type of conversation unit	All groups	Early	Middle	Late
	Frequency of units	Groups, *f* (%)		
Relational reasoning	228	83 (36.4)	94 (41.2)	51 (22.4)
Analogy	140	60 (42.9)	53 (37.9)	27 (19.3)
Anomaly	30	13 (43.3)	12 (40)	5 (16.7)
Antinomy	31	5 (16.1)	16 (51.6)	10 (32.3)
Antithesis	27	5 (18.5)	13 (48.2)	9 (33.3)

Relational reasoning by object. In addition, we examined the frequency and distribution of relational reasoning units according to object familiarity (Table 4). Specifically, students produced a total of 107 relational reasoning units about the familiar object and 121 units pertaining to the unfamiliar object. Therefore, 47% of the total observed 228 relational reasoning units were produced about the familiar object, while 53% were produced about the unfamiliar object. To ascertain whether or not these observed proportions were significantly different from what would be theoretically expected, a χ^2 was utilized. The nonsignificance of this test, $\chi^2(3) = .86$, $p = .35$, indicates that there was not a generalizable difference in the proportion of relational reasoning units produced between the familiar and unfamiliar objects.

It is important that although this test does suggest that general relational reasoning usage across all four forms of the construct was not statistically equivalent between the familiar and unfamiliar object, the question remains: Was the proportionate use of the four forms of relational reasoning consistent across these conditions? To address this question, an omnibus χ^2 test was used to compare the observed proportions of the relational reasoning forms between the familiar and unfamiliar objects, $\chi^2(3) = 78.87$, $p < .001$. The significance of this test indicates that the observed proportions of relational reasoning forms between the conditions were significantly different from one another. This finding implies that the familiarity of the object being reasoned about, while not significantly affecting the frequency of total relational reasoning units as indicated earlier, did potentially influence the form of relational reasoning used.

Specifically, of the 107 units concerned with the familiar object (i.e., juice box), 45.8% (n = 49) were analogical in nature, 15.9% (n = 17) were anomalous, 16.8% (n = 18) were antinomous, and 21.5% (n = 23) were antithetical. A significant chi-square test of goodness of fit indicated that these proportions were significantly different than what would be theoretically expected, $\chi^2(3) = 25.45$, $p < .001$. Specifically, analogical reasoning accounted for about half of the reasoning units about the familiar object, and the other three forms occurred proportionately less.

Table 4
Frequency of Relational Reasoning Units by Object Familiarity

Form	Total	Early	Middle	Late
	f (%)	Cohorts		
Familiar object				
Relational reasoning	107	34	53	20
Analogy	49 (45.8)	17 (50)	24 (45.3)	8 (40)
Anomaly	17 (15.9)	8 (23.5)	9 (17)	0 (0)
Antinomy	18 (16.8)	5 (14.7)	8 (15.1)	5 (25)
Antithesis	23 (21.5)	4 (11.8)	12 (22.6)	7 (35)
Unfamiliar object				
Relational reasoning	121	49	41	31
Analogy	91 (75.2)	43 (87.8)	29 (70.7)	19 (61.3)
Anomaly	15 (12.4)	5 (10.2)	5 (12.2)	5 (16.1)
Antinomy	9 (7.4)	0 (0)	4 (9.8)	5 (16.1)
Antithesis	6 (5.0)	1 (2.0)	3 (7.3)	2 (6.5)

For instance, questions about why the product had been developed often elicited analogical statements related to what the object actually was, given that identifying the object, or, what the object was like, was a necessary precondition to describing why it might have been designed. As a case in point, one student said that the juice box had been developed "for people to drink at school," and analogically reasoned that this was because "it's like a little snack." Other questions related to the quality of packaging or the object's degree of "fitness for purpose," tended to elicit more anomalous, antinomous, and antithetical statements. One student, remarking that the packaging was not "long term," explained herself with an antithetical statement: "It's not something that would last for years, it's something [for] just on a trip, maybe, a car trip, a picnic." Another student used an antinomous statement in arguing that the object was "fit for purpose, but it's probably not fit for our world, as in, being biodegradable and carbon neutral." Thus, while AGs were used to provide background about the identity of the object, AMs, ANs, and ATs seemed to function as supports for students' arguments about the function, quality, and design of the product.

Unlike the distribution of relational reasoning units for the familiar object, over 75% ($n = 91$) of the relational reasoning units produced in reference to the vegetable cutter were analogical. A relatively fewer percentage were anomalous (12.4%; $n = 15$), antinomous (7.4%; $n = 9$), and antithetical (5%; $n = 6$). A chi-square test of goodness of fit confirmed that the forms of relational reasoning were not used proportionately equally, $\chi^2(3) = 164.06, p < .001$. Potentially because the vegetable cutter was highly unfamiliar, students typically spent the majority of the conversation trying to determine what the object and its purpose were—a process where AGs may have been critical. Thus, while the range of AGs generated by younger and older students varied from simple statements (e.g., "It's like a car") to more complex statements (e.g., "It could be a kind of blender; a blender is the first thing to comes to mind, with the blades"), very few students used other types of relational reasoning unless they were qualifying statements they had made about the object's identity.

For instance, one student used an AN in reference to the unfamiliar object, explaining, "I *wouldn't* say it's a toy because it's sharp [emphasis added]." Another used an AM in reasoning that the unfamiliar object was designed for "people who cook at home, cause there are probably commercial ones and they probably [chop things up] *differently* [emphasis added]." Considering that AMs, ANs, and ATs occurred relatively less often than AGs, it is possible that students relied on AGs as a first course of action because of their paucity of direct knowledge of or experience with a focal object.

It is interesting that while the relational reasoning about the unfamiliar object was dominated by AGs (75%), the reasoning about the familiar object was comparatively more evenly distributed, with only about 45% being attributable to AGs. This pattern of relational reasoning may naturally arise in discourse, because of the foundational requirement of relational similarity for students' understanding of unfamiliar objects or ideas (Dumas et al., 2014; Hofstadter, 2001).

Developmental Differences in Relational Reasoning

Overall distribution of relational reasoning units. We next examined the differences in the relative proportions of relational reasoning verbalizations by age. In an attempt to probe the unequal frequencies of the forms of relational reasoning and the larger developmental differences in relational reasoning forms, grade levels were collapsed into three groups—early, middle, and late—corresponding to key points in development (Giofrè, Mammarella, Ronconi, & Cornoldi, 2013; Hu, Shi, Han, Wang, & Adey, 2010). Grades K, 2, and 4 comprised the early group (age range = 5 to 10); grades 6 and 8 were combined for the middle group (age range = 11 to 14); and grades 10 and 11 comprised the late group (age range = 15 to 17).

For this question, we compared the observed proportions of verbalizations of each form against a null distribution via χ^2 analysis. Because the counted conversation units being examined in this analysis could not reasonably be expected to approximate normality (Winkelmann & Zimmerman, 1995), and our research questions specifically dealt with issues of proportional distributions, a nonparametric approach to analysis was deemed appropriate. Specifically, expected values for each condition were calculated by taking into account the number of students in each group, and hypothesizing a null distribution under which each student in each cohort would make an equal contribution to the overall count of relational reasoning verbalizations. In this way, our analysis focused on whether or not the distribution of reasoning units across age-related groups was even, or whether membership in a particular group affected the observed distribution of reasoning in a significant way. Such nonparametric analyses have proven fruitful in past investigations of real-time reasoning, and have been shown to be an effective way of capturing proportional differences in the use of reasoning types over time (e.g., Christensen & Schunn, 2007; Dumas et al., 2014).

With the students divided into developmental groups, we examined the differences between the observed frequencies of relational reasoning units and the frequencies that would be statistically expected under a null distribution in which each group contributed equally. (See Figure 2 for an illustration of the differences in the proportions of reasoning units across the groups.) The analysis revealed that the groups did not contribute equally to the total relational reasoning units, $\chi^2(2, N = 228) = 7.42, p < .05$. It is important that the observed frequency of relational reasoning units differed from the expected distribution in different directions depending on the group. Specifically, while the early and late cohorts verbalized fewer relational reasoning units than statistically ex-

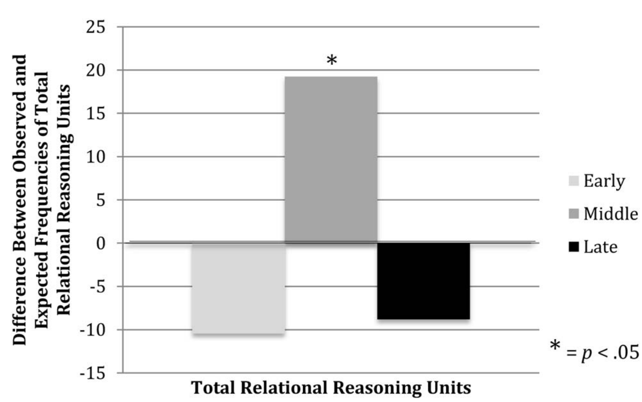

Figure 2. Difference in observed and statistically expected frequencies of total relational reasoning units by age group.

pected, the middle cohort verbalized more. In this way, a curvilinear developmental trajectory in the observed frequency of relational units was uncovered, such that the middle group verbalized a significantly greater proportion of relational units than either the early or late group. More precisely, the observed frequencies of relational units for the early and late groups were similarly about 10 units below what was statistically expected, while the observed frequency of relational units for the middle group was 20 units more than what was expected.

Differences in relational reasoning forms within and across developmental groups. Next, we sought to examine the differences in relative usage of each particular form of relational reasoning in each developmental age group. Again, we accounted for sample size as we formulated statistically expected proportions across the early, middle, and late groups, and compared them with the observed proportions. Individual χ^2 tests for goodness-of-fit were then carried out for each relational form to examine how the relative proportions of verbalizations changed across the three groups. These tests showed significant differences in all four forms of relational reasoning. In particular, we observed distributions containing significantly fewer AGs, $\chi^2(2) = 9.29$, $p < .01$, and AMs, $\chi^2(2) = 12.6$, $p < .01$, than would be expected, and significantly more ANs, $\chi^2(2) = 18.95$, $p < .001$, and ATs, $\chi^2(2) = 13.23$, $p < .01$, than would be expected. It is important that, as illustrated in Figure 3, the middle group produced more units of each form of relational reasoning than would be statistically expected; however, in the late group, this pattern diverged. Specifically, the late group produced fewer AGs and AMs than would be statistically expected, while the group produced more ANs and ATs than statistically expected.

Based on previous analyses of the four forms of relational reasoning as demonstrated in real-time discourse (e.g., Dumas et al., 2014), we have reason to believe that these forms may not operate in complete isolation. Rather, particular forms may operate in concert, depending on the task.

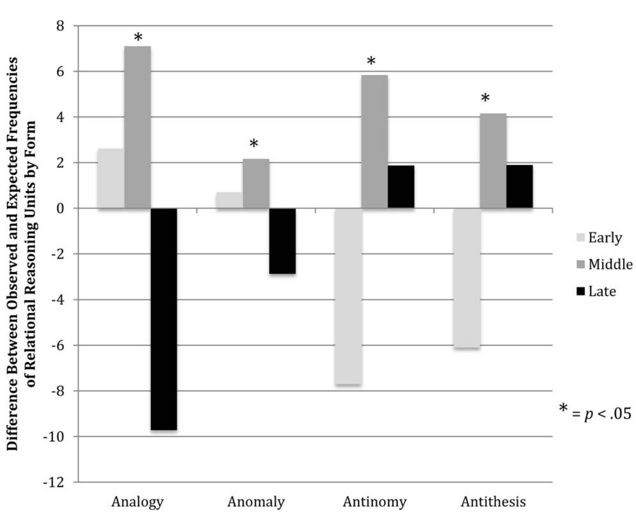

Figure 3. Difference in observed and statistically expected frequencies of forms of relational reasoning units by age group.

Extent of Researcher Support by Student Age

While the previous analysis established the ability of students of various ages (i.e., 5 to 17 years old) to verbalize the four forms of relational reasoning, it is important to consider the extent to which the support of more knowledgeable other (i.e., researcher) may have contributed to these verbalization patterns. To understand the occurrence and development of relational reasoning in this study, we must appreciate that the reasoning events were part of a semistructured conversation between student and researcher. By investigating those reasoning units in conjunction with the amount of verbal support provided by the researcher, we have a clearer sense of the degree to which scaffolding may have contributed to the patterns we identified. Thus, similarly to our developmental questions, we conducted a nonparametric analysis test to compare the proportion of student to researcher talk across ages and objects.

Again, nonparametric testing was considered ideal in order to get at the differences in the *ratio* of student to researcher talk, rather than differences in raw word counts. Results showed that this proportion of talk varied significantly by the age of the student, $\chi^2(6) = 22.27$, $p < .01$, such that researcher talk accounted for about 60% of the conversation units for the youngest students, but steadily decreased until it accounted for only 38% for the oldest students (Table 5; Figure 4). This pattern held both for the familiar, $\chi^2(6) = 20.46$, $p < .01$, and unfamiliar objects, $\chi^2(6) = 25.43$, $p < .001$, demonstrating a consistent and significant withdrawal of researcher verbal support across the grade levels.

To illustrate, with the youngest children, the researcher would start by asking what the familiar object (i.e., a juice box) was and follow up with pointed questions about what it was made of, why it was made it like that, and how the juice got into the box. This approach allowed the researcher to break down complex questions (e.g., "Why was this product developed?") into something more cognitively manageable for the younger children. With children in the middle and late groups, however, the researcher would simply open by asking why the product had been developed, with the assumption that these students already knew what the object was.

There were also instances in which the researcher restated something unclear the child had said. As a case in point, one second-grade child remarked that the juice box was made out of "hard stuff," presumably referring to plastic. The researcher replied, "Hard stuff? Do you know the name for that hard stuff? Why do you think it was hard stuff? Why do you think they used hard stuff?" As a result, the researcher tended to speak more with younger children who had less experience with the focal objects. This type of researcher elaboration occurred far less with older students, who generally had more knowledge about the objects and were more articulate with their thoughts. Thus, as predicted, there was a greater proportion of researcher to student talk when students were younger and less knowledgeable about the objects and task domain.

It is interesting that the general trend of an increasing student-to-researcher talk ratio was slightly complicated by the second grade students in this sample. Upon further scrutiny, we found that although these students spoke proportionally less than their teachers, their talk was more task-related (74.6% compared with 65.3%) and less off-task (16.8% compared with 21.2%) than the talk of kindergarten children. Given the increases in executive functioning

Table 5
Word Counts by Grade and Object Type

	Grade, *f* (%)						
	K	2	4	6	8	10	11
Familiar							
Student	974 (41)	728 (35)	2,070 (51%)	2,006 (52)	2,651 (54)	2,460 (58)	1,614 (61)
Researcher	1,410 (59)	1,325 (65)	1,961 (49%)	1,877 (48)	2,299 (46)	1,747 (42)	1,039 (39)
Unfamiliar							
Student	707 (41)	357 (32)	1,105 (51%)	1,025 (49)	1,538 (56)	1,442 (55)	1,272 (63)
Researcher	1,014 (59)	772 (68)	1,302 (49%)	1,085 (51)	1,192 (44)	1,195 (45)	748 (37)

and capacity for attention that develop between kindergarten and second grade (Deater-Deckard, Petrill, Thompson, & DeThorne, 2006), it is possible that in this instance the proportion of student-to-researcher talk among second graders belied the type of the manifested.

Conclusions and Implications

As the results of this study suggest, the quality and quantity of relational talk vary widely among students of different ages. Specifically, there is evidence to support the notion that certain forms of relational reasoning become more and less prevalent in student discourse at various ages. More broadly, however, this study is, to our knowledge, the first of its kind to depict a large-scale, cross-sectional picture of the usage of relational reasoning by analyzing real-time conversations. Only by our proportional analyses of the relative forms and frequencies of relational reasoning units as well as counts of researcher and student talk were we able to discern such a portrait. As a consequence of these analyses, we were able to uncover several findings of theoretical and practical interest.

Young Children Are Capable of Reasoning Relationally

One of those findings concerns the capacity of young children to reason relationally. The literature had long been torn on whether young children were cognitively capable of constructing higher-order relations such as those required to comprehend AGs (Gentner, 1977; Levinson & Carpenter, 1974). Some researchers argued that analogical reasoning is an ability reserved for children over the age of 9 (e.g., Levinson & Carpenter, 1974), while others found evidence of such reasoning in children of preschool age (e.g., White & Alexander, 1986). In this study, there was an opportunity to look anew at this longstanding debate, but more importantly, to extend examination of children's reasoning capacities to varied forms of relational reasoning and to test for that in more conversational exchanges.

Thus, one of our goals in this study was to explore evidence that would either support or refute the premise that even young children are capable of reasoning relationally. Given that our study involved a methodology requiring subjects to verbalize their thoughts in a conversational forum, as opposed to solving highly structured spatial relational problems (e.g., Eslinger et al., 2009; Gentner, 1977; Raven, 1938), we remained uncertain as to the outcome. In addition, the complex task domain of technological literacy, coupled with the presence of more and less familiar objects, further caused us to question the possibility that we would observe relational reasoning, at least in our youngest participants.

In fact, we found that even our youngest students (i.e., five year-olds) were capable of relational reasoning. These children demonstrated not only analogical reasoning, but anomalous, antinomous, and antithetical reasoning as well. Yet, there were nuances in the ways in which these forms of reasoning manifested themselves. For instance, based on a proportional analysis, children in the early grades demonstrated fewer instances of relational reasoning than would be expected statistically, and fewer instances than children in the middle grades—although such a pattern may make sense developmentally. In addition, the youngest children's relational reasoning was predominantly analogical in nature, although there were, to a lesser degree, instances of the other three forms. Similarly, the unfamiliar object prompted a significantly greater proportion of analogical utterances than did the familiar object. Thus, it is possible that young children default to comparisons of likeness when confronted with unknown objects or ideas.

In understanding these results, it is important to acknowledge the context in which these students were reasoning. The fact that they were engaged in discourse with another individual may have afforded them the opportunity of benefitting from the knowledge and experience of a more knowledgeable other. Specifically, researchers may have inadvertently scaffolded complex technological literacy concepts for the young students and, therefore, contributed to those students' relational reasoning. Although we cannot speak to whether or not students as young as 5 would have been able to spontaneously produce instances of the four forms of relational reasoning when completely alone, we were able to

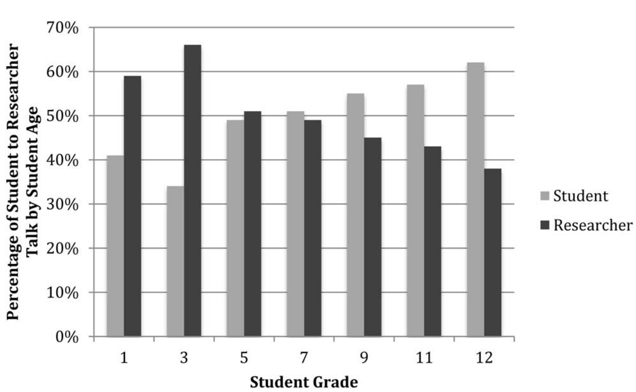

Figure 4. Student to researcher talk ratio by year.

support arguments in favor of young children's ability to reason not only analogically in semistructured conversations, but anomalously, antinomously, and antithetically.

Relational Reasoning Manifests Differently at Different Ages

Contrasting the patterns of relational reasoning of the early group with the middle and late groups, it also became clear that the occurrence of specific relational reasoning forms differed for children of different ages. Of particular interest to us was the curvilinear trajectory in the frequency of relational reasoning verbalizations among the students. Specifically, the early and late groups demonstrated significantly fewer instances of relational reasoning than expected, while the middle group demonstrated significantly more. Whether or not the capacity for relational reasoning is more advanced in older children, it is clear that older age per se does not guarantee the increased usage of more relational reasoning units.

Alexander's (1997) MDL may offer a partial account of the aforementioned developmental pattern. In effect, the early and middle groups appeared to fall in the respective stages of early to late acclimation, demonstrating increased knowledge and strategic processing, marked by increasing frequencies of relational reasoning. By this logic, we might expect the late group to use even greater amounts of relational reasoning than the other two groups, demonstrative of their well-developed knowledge base and relational reasoning skills. However, we found the opposite. In fact, these older students verbalized fewer instances of relational reasoning than those in the middle group. Again drawing on the MDL, we can forward two plausible explanations. First, it is possible that fewer instances of relational reasoning within the late group could have been indicative of competency in terms of knowledge and strategic processing, such that these students were more judicious in their use of relational reasoning. Alternatively, this curvilinear pattern may reflect the older students' increased familiarity with the target objects and with the task domain, thus reducing their need to reason relationally.

Put differently, the older students in this study may not have needed to verbalize relational reasoning to address the researcher's questions about form and function and good design. That is to say, younger students may have used relational reasoning to bolster their arguments as to why, for instance, the juice box was an example of good design (e.g., "They've made it . . . so it's made people's lives easier if they take that because it's *easy to carry around instead of taking a big juice bottle*" [sixth-grader ATs, emphasis added]). The older students, by comparison, may have felt able to provide justification without the need for relational reasoning (e.g., "It does exactly what it's supposed to do. Make juice easily accessible for younger children, I suppose" [tenth grader]). In this way, the curvilinear pattern in reasoning observed suggests that too little knowledge of object or task can hamper relational reasoning, whereas an abundance of object or task knowledge could reduce the need for such reasoning, as has been indicated for other cases of strategy by knowledge interactions (Alexander & Judy, 1988). This may have been especially true for the students who came into the semistructured conversation with some knowledge of the function of the unfamiliar object (six of whom belonged to the oldest cohort of students).

As an alternative, the unexpected decrease in relational reasoning in the Late group may reflect physiological changes that occur naturally with age. Researchers have documented a concurrent increase in relational reasoning accuracy and concomitant decrease in neural activation in brain structures (e.g., rostrolateral prefrontal cortex; Crone et al., 2009; Dumontheil, Houlton, Christoff, & Blakemore, 2010) associated with this ability during adolescence. These results may indicate that relational reasoning becomes more cognitively manageable for older adolescents, such that they do not need to spend as much time effortfully engaged in relational reasoning, and that the relational reasoning they do is not as cognitively demanding. In the context of this study, it is plausible that older students were competent enough in their relational reasoning to discuss the form and function of each object without need for further elaboration, whereas younger students may have used more elaborated instances of relational reasoning to emphasize a point. However, this is a phenomenon that cannot be specifically tested in the present investigation. As a consequence, future research in which knowledge and strategic processing are varied systematically is needed to elucidate the curvilinear pattern for relational reasoning uncovered in this investigation.

Trajectories of Individual Forms of Relational Reasoning

In addition to differences in the frequencies of relational reasoning, there were variations among the groups in the prevalence of the different forms. For instance, whereas the proportions of, ANs and ATs increased in the middle and late groups, the proportions of AGs and AMs decreased significantly among the three groups. Given that AGs are seen as an initial organizing principle in developing an understanding of an object or concept (Gentner & Rattermann, 1991), it is unsurprising that children in the early group used them with such great frequency. Similarly, AMs may have allowed children to make basic categorizations about the objects as being one of a "set" of particular items. Thus, in the absence of more complex reasoning strategies involving relations of negation and identifications of boundaries between objects or concepts (i.e., ANs and ATs), AGs and AMs may have served as global judgments of similarity and difference.

For the oldest children, by contrast, ANs and ATs occupied a greater proportion of relational talk. As others have suggested, it is possible that ANs and ATs represent more complex forms of reasoning that may be more easily demonstrated by older children (Dumas et al., 2013). These children may be more neurologically capable of reasoning in such ways, having more developed brain structures that allow them to integrate multiple relations simultaneously (Crone et al., 2009; Eslinger et al., 2009).

However, older students may also benefit from having had greater experience with the task domain of technological literacy, or simply with schooled activities in which argumentation is central. Given that the students in this study were asked to justify their assessments of objects' levels of fitness for purpose, older students may have drawn on skills gained from classification or refutational activities (Taverna & Peralta, 2013; van den Broek & Kendeou, 2008), resulting in greater proportions of ANs and ATs. In this way, older students' mental hardware and software may have been implicated in the ways in which their relational talk was expressed.

Alternatively, it is possible that the oldest students were using AGs and AMs in reasoning, but primarily in thought, verbalizing only a small proportion of these forms and more in the way of ANs and ATs. As such, AGs and AMs may be habituated reasoning strategies for children in high school, mainly helping to support the verbalization of more complicated thoughts and arguments (Vygotsky, 1962, 1978).

However, the task context must also be considered in the explanation of current results. It is possible that in spite of the relative ease or difficulty with which certain relations were made by children of different ages, the nature of the task itself elicited particular forms of relational reasoning. For instance, asking students to identify an unfamiliar object may have prompted analogical reasoning, since one way of identifying a foreign object might involve drawing connections between that object and other similar objects. In this way, the relative scarcity of antinomous reasoning especially among the younger participants may be unsurprising, as eliminating what the object could not be might not have been the most efficient way of identifying what it actually was.

Given our finding that the oldest students verbalized relatively more ANs and ATs, however, we do have some sense that these students were more facile at drawing connections beyond that of AG. Moreover, these older students appeared to be more competent at using a range of relational reasoning strategies to address the interviewers' questions about the objects. Although we cannot disentangle the task from the developmental capabilities of children of different ages, we do posit that relational capacity, as well as the context in which that reasoning is situated, appears to contribute to the quality and quantity of relations that are manifested.

Patterns of Emergence of the Forms of Relational Reasoning

Over and above the varied configurations of knowledge of and experience with the objects and task domain, coupled with the relational reasoning abilities of the children in the three groups we identified, we saw evidence of an emerging sequence among the differing relational reasoning forms. If, for instance, the pervasiveness of AGs among the youngest children, and subsequent decrease in older children, was related to the children's knowledge base about the objects or task domain, then AGs may indeed function as an initial step when confronting a reasoning task. This is reasonable, given that establishing what an object is *like* may segue to discussing how it differs from the norm (i.e., AM), from which categories it can be excluded (i.e., AN), and from which objects it operates in opposition (i.e., AT; Gentner & Rattermann, 1991). Thus, AMs, ANs, and ATs may manifest once initial similarity judgments are forwarded.

Only one study, to our knowledge, has investigated the ways in which these four forms of relational reasoning unfold collectively in discourse (Dumas et al., 2014). By creating a transition matrix in which the frequencies and transitions among forms of relational reasoning were analyzed, these researchers found that certain forms clustered together, and certain forms tended to precede or succeed others. Although the contexts are not directly comparable, as our study dealt with schoolchildren's reasoning about technological form and function, and the Dumas et al. (2014) study dealt with doctors' diagnostic and therapeutic decision-making, it is reasonable that certain forms of relational reasoning may operate in concert in children's discourse. Specifically, the proportions of both AGs and AMs, and ANs and ATs, appeared to change in the same ways. Although the development of relational reasoning was the focus of this paper, an exploration of the systematic unfolding of relational reasoning among children of different ages seems a logical next step in analyses.

Presence of Scaffolding

In addition to the contributions of children's knowledge of the object and task domain, and maturational changes they may undergo, it is crucial to consider the potential impact of the research context in which this study was conducted on the relational reasoning demonstrated by these children. Rather than assessing relational reasoning with spatial tasks or written word problems, we chose to immerse children in semistructured conversations with a researcher in order to see how instances of relational reasoning would manifest without explicit prompting. We were also interested in seeing whether the researcher might function as a "more knowledgeable other," or an individual who could scaffold complex concepts, such as technological form and function. Previous research has suggested that participation in social interaction may bolster reasoning skills (Piaget, 1928), and, further, that interactions with a more knowledgeable other can help scaffold skills that an individual would not be capable of on his or her own (Vygotsky, 1978). More recent research on these naturally occurring experiences has yielded the notion of a "critical-analytic stance," in which a more knowledgeable other attempts to engage a pupil in questioning to promote reasoning and argumentation skills (Chinn, Anderson, & Waggoner, 2001; Murphy et al., 2009).

In terms of the current study, it could be argued that the researcher functioned as a more knowledgeable-other and engaged students in meaningful conversations about technological form and function that prompted students to reason relationally. In addition, the researcher may have adjusted the content or amount of her talk to a level that was appropriate given the age or reasoning ability of the child. Our analysis of the relative contributions of child and researcher to these conversations indicated that researchers spoke a majority of the time with the youngest children, a comparable amount with those in the middle, and only a small portion of the time with the oldest. This shift in proportion of talk may have been indicative of a gradual release of responsibility according to the age and abilities of the child (Vygotsky, 1978).

It may be that, with the support of the researcher, even the least knowledgeable or least cognitively developed children are enabled to manifest instances of relational reasoning. If this was indeed the case, then it becomes critical to consider the affordances of the external environment when evaluating the higher-order reasoning skills of children of various ages. Similarly, practicing teachers may consider altering the quality and quantity of their talk for students with poor relational reasoning skills.

Limitations and Future Research

Although the cross-sectional nature of this study allows us to draw several conclusions about the relative capabilities of students' relational reasoning at different ages, a longitudinal study would allow us to make more definitive statements about the nature and development of relational reasoning. For instance, would the same curvilinear developmental pattern hold over time or in the presence of more explicit training and experiences? Such a study would be instrumental in enabling us to observe the changes individual students undergo over time. In addition, this might help to substantiate current findings, given the relatively small sample size of 61 participants. The ability to make generalizations about developments in students' relational reasoning is somewhat limited for this investigation, even when grade levels are collapsed into developmental groups. Thus, observing students at a second point in time would enhance the strength and generalizability of present findings. An examination of relational reasoning in experts in the field of technology would similarly add to the portrait of relational reasoning uncovered here and contribute to expert validation of the relational reasoning construct.

As an alternative, an intervention study might give us insights into the malleability of relational reasoning capabilities for students of various ages. For example, with explicit training on relational reasoning, could young children manifest the same types of reasoning patterns as older students? Relational reasoning interventions have been conducted successfully in the past, even with children as young as 4 years old (White & Alexander, 1986). However, whether or not an intervention focused on relational reasoning in its varied forms would be successful at improving such skills as observed in discourse, remains to be seen.

In addition, the lack of counterbalancing in object presentation may have played a role in the way that children responded to the unfamiliar object. Specifically, it is possible that the experience gained from reasoning about the familiar object allowed students to more easily interact with the unfamiliar object, and to express different forms of relational reasoning than they otherwise might have. Although we believed that presenting the familiar object first would help to orient students to this novel task and subsequently help them feel efficacious enough to engage, we cannot be sure that there was no order effect.

It is clear that a number of variables influence the ways in which students' relational reasoning manifest in discourse, among them, knowledge of objects and task domain, cognitive development, and affordances from the external environment (e.g., scaffolding from a more knowledgeable other). Thus, future empirical research is needed to disentangle the relative contributions of such factors. In spite of these lingering questions, practicing teachers stand to benefit greatly by considering the interplay of these factors within their classrooms. With a greater understanding of the influences on their students' relational reasoning, teachers may be able to target struggling students and devise strategies to help them develop this important cognitive capacity. More broadly, given the pivotal role of relational reasoning in the development of higher cognition (Halford, Wilson, & Phillips, 1998), this research has the potential to influence both educational research and practice in important ways.

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