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Conceptual coherence revealed in multi-modal representations of astronomy knowledge

Abstract

The astronomy concepts of 345 young people were studied over a 10-year-period using a multi-media, multi-modal methodology in a research design where survey participants were interviewed three times and control subjects were interviewed twice. The purpose of the research was to search for evidence to clarify competing theories on *conceptual coherence* versus *knowledge-in-pieces*, distinguishing between coherence as revealed in the representational systems at any particular stage in a young person's development and the changes evident in mental growth thereafter. Thus five research questions concerned with the elements and structure of understanding were investigated: (a) conceptual coherence shown as patterns of high *correlation* of concept representations between the media used to assess subjects' understanding *within* a survey, as well as (b) coherence revealed as *consistency* of representation of those concepts across media and modalities; (c) enhanced conceptual understanding and skill through repeated interviews *across* (longitudinal) surveys, as young people develop their knowledge; (d) cultural similarity in subjects' representations of *basic static concepts* (e.g. the shape of the Earth); and (e) improved understanding of *basic dynamic concepts* (e.g. the motion of the Earth) and *complex dynamic concepts* (e.g. seasons and eclipses), through 'knowledge-skill compounding' (c.f. Barsalou, 2003). The research findings supported *conceptual coherence* and rejected the counter argument of *knowledge-in-pieces* (at an alpha level of .05). Further research is recommended to replicate current research in cultures other than those of China and New Zealand studied here to confirm the view that cognition and knowledge are inherently coherent in young people.

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Conceptual coherence in multi-modal representations

Introduction

Research in science education on the relationship between intuitive and scientific physics, exemplified by comparisons between children's cosmologies and the world view of scientifically literate adults, has been the focus of rich seminal research. There are currently two strongly opposing views of both the fundamental form of the elements of children's ideas and also the degree of organisation of their elements into coherent cognitive structures. On the one hand, there are those who believe that children's ideas are in the form of concept*s* - which differ from adult concepts only in degree of scientific accuracy - and which are organised into coherent theory-like structures - akin to adult theories but less precise scientifically (see Carey, 1985, 1991; Chi & Slotta, 1993; Donaldson, 1976, 1978; McCloskey, 1983; Vosniadou, Vamvakoussi, & Skopeliti, 2008; Authors, 2006a and 2006b). As Murphy and Medin (1985) stated in their early paper on conceptual coherence: "The keystone of our explanation is that people's theories of the world embody conceptual knowledge and that their conceptual organization is partly represented in their theories" (pp. 289-290). This view is reiterated in modern terms by Vosniadou et al. (2008):"At the heart of our theoretical approach is the idea that initial explanations of the physical world in naïve physics are not fragmented observations but form a coherent whole, a framework theory" (p. 4).

On the other hand, there are those who believe that children's ideas are composed of fragmented pieces of knowledge (phenomenological primitives or p-prims) which are only loosely connected and lack the features (commitment or systematicity) characteristic of scientific theories (see diSessa, 2008). He summarised his argument: "From a knowledge in pieces point of view, "intuitive theories," if they exist, are highly aggregated; I project that we will not be able to describe conceptual change at all perspicuously from such a high level of aggregation. Only with a more appropriate, sub-conceptual grain size can we describe the

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structure (and in consequence define and evaluate coherence) of naïve ideas, and only at that level can we track the reconstitution of naïve elements into normative concepts" (p. 38).

The studies reported here attempt to illuminate this ongoing debate on the structure of children's knowledge through a research design and analysis which goes beyond that which the present authors have reported in Authors 2006b; permits a testing of newer theories of what conceptualisation amounts to; and endeavours to resolve the differences between what is detectably coherent in the representational systems at any particular stage in a young person's development and the changes evident in mental growth thereafter. The research was based on interactions with young people (children and young adults) to ascertain their astronomical and Earth science concepts through the media of verbal language, drawing and play-dough modelling. This involves representation of the physical world, a cognitive process recognised to be an important factor in knowledge acquisition, and one which depends on modelling reality with varying degrees of accuracy. Mandler (1998), in an extensive review, considers representation as knowledge stored in memory in a distinct representational format. One of these is mental imagery - either static (e.g., where the subject perceives the shape of an object such as the Sun) or dynamic (e.g., where the subject brings about a mental rotation of several objects, for example, imagining the movement of the Earth around the Sun) – these being located in the visuo-spatial and motor areas of the brain (see Richter, Somorjai, Summers, Jarmasz, Menon, Gati, Georgopoulos, Tegeler, Ugurbil, & Kim, 2000). The understanding of two complex dynamic phenomena by children and young adults – seasons and eclipses – was studied in the longitudinal research described here, the fieldwork being conducted in China and New Zealand, these countries having rich astronomical traditions.

Concepts as skills

However, it is important to recognise that new theories question the idea of concepts as representations and posit them not as models of reality such as mental models (see Gentner

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& Stevens, 1983; Johnson-Laird, 1983) but rather as simulators or skills in creating such images consistently over a range of modal stimuli and responses (see Barsalou, 2003). This alternative view of a concept as a creative ability rather than as simple recall from memory has important consequences for research methodology. Researchers who gather empirical data from interviews and surveys have more to clarify in respect of what is detectable, conceptually, in exchanges with subjects and what actually develops with the passage of time and exposure to life. Viewing concepts as skills also raises questions about repeated measures using interviews, since interview questions may lead to enhanced conceptual skill, and any longitudinal research design should take this into account (see Cromer, 1987; Kuhl, 2000). Some theorists even go as far as to consider "the notion of representation to be dispensable" (van Gelder, 1998, p. 622). This paper considers both the representational sense and the skill interpretation of concepts and emphasises the dual nature of coherence: (1) as an inherent feature of cognition to make sense of the world; and (2) as a fine tuning system which enables the thinker to process and respond to multiple sensory modalities (as when recognising old and creating new conceptual representations) which complement each other. We argue that this complementarity reinforces the power of the multi-modal methodology used in the research. 'Modalities' refers to different ways of sharing meaning, a term used in cognitive neuro-science where different abilities, senses and muscles convey understanding or connotation. Thus 'media' are the materials of expression, such as speaking, drawing or modelling with play-dough; and 'modalities' are the thought processes and muscular skills that are used to shape materials, say, into a form analogous to a verbal concept.

Previous research: the cross-cultural literature

Findings from different strands of research require to be considered in order to establish pertinent aims and hypotheses, as well as variables to be explored in accounting for survey findings about children's thinking. These are set out under three headings.

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Conceptual coherence in multi-modal representations

Research on children's conceptual development

*The domains of astronomy and Earth science have long attracted researchers into conceptual development and intuitive theory formation both within and across cultures (see Authors, 2006a, 2006b, 2007). The general features of children's concepts of Earth's shape and gravity have been studied extensively, seminal work being done by Nussbaum (1979): Nussbaum and Novak (1976); Piaget (1929, 1930); Sneider and Pulos (1983); and Vosniadou and Brewer (1992, 1994). For a recent review, see Agan and Sneider (2004). Investigations into young people's ideas of dynamic relationships between astronomical bodies such as the motion of the Earth-Moon-Sun system have also featured in research including studies of seasons and eclipses. The latter are of particular interest in that their explanation requires an understanding of both the shape and relative motion of the Earth, Sun and Moon. With regard to the seasons, young people's concepts have been studied in: (a) Australia, by Lucas & Cohen (1999); (b) England, by Baxter (1989); (c) Estonia, by Kikas (1998); (d) Greece, by Bakas and Mikropoulos (2003); (e) Israel, by Elhanan, Yoav and Chen (2005); (f) Switzerland, by Piaget (1929, 1930); and (g) USA, by Furuness and Cohen (1989); Rollins, Denton and Janke (1983); Sadler (1992); Schneps and Sadler (1987); and Schoon (1989). Understanding of eclipses has been investigated in: (a) China, by Dai (1991); (b) Israel, by Elhanan et al. (2005); and (c) USA, by Barnett and Morran (2002); and Riddle (1993, 1996).

From all of these studies, we can conclude that understanding of complex dynamic phenomena such as seasons and eclipses is a measure of both astronomical knowledge (in the form of a theory-like structure) and conceptual coherence (as skill in creating and combining concepts). It involves scientific understanding of cosmological elements (such as the shape and motion of the Earth, Sun and Moon) and the ability to mentally manipulate these concepts in unison to create the essential features of seasons and eclipses spatially and from the perspective of an observer on Earth.

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Research on teachers and the curriculum

Researching the development of children's thinking in these areas requires two important contextual considerations to be taken into account. One is concerned with their teachers' understandings, the other with what figures in relevant school curricula and what is taught. With respect to the first of these, the astronomy and Earth science concepts of pre-service teachers and practising teachers have been surveyed to ascertain competency: (a) in China, by Dai and Capie (1990); (b) in Finland, by Ojala (1997); (c) in Israel, by Trumper (2006); (d) in NZ, by Ministry of Education (2000); (e) in Turkey, by Ogan-Berkiroglu (2007); (f) in UK, by King (2001); and Mant and Summers (1993); (g) in USA, by Atwood and Atwood (1997); Schoon (1995); and Schneps and Sadler (1987). These studies have shown that pre-service and practising teachers have inadequate background knowledge in science and lack confidence in teaching astronomy and Earth science topics such as the motion of the Earth-Moon-Sun system, seasons and eclipses.

With regard to what is taught to children in various countries, broadly similar treatments are given to astronomy and Earth science concepts but there are variations. Thus:

1. Janke and Pella (1972) identified the concepts recommended by scholars of Earth science and scientists for inclusion in the US K-12 science curriculum. The final list had fifty-two items: the highest scoring concept being *seasons*; and the fifth *day and night*.

2. Rollins, Denton and Janke (1983), in the USA, investigated the attainment of Earth science concepts by high school seniors. They found significant differences in concept achievement which they attributed to the quantity of coursework completed.

3. Agan and Sneider (2004) reviewed the astronomy and Earth science curriculum in the USA by comparing the recommendations of the National Research Council (1996) with the educational goals of the NASA Office of Space Science; and curriculum materials being prepared by The Scott Foresman Science Series. They conclude by recommending that

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elementary science texts be revised in line with national curriculum standards; e.g., that science curriculum editors should "Eliminate from the text for grades one through three explanations of astronomical phenomena that require students to understand the Earth's spherical shape and gravity concepts"; and replace these with "activities in which students observe, record, and find patterns in the world around them". They believe that formal teaching of Earth shape and gravity concepts should be delayed until grades 4-5 when "students can begin to construct a model that explains the visual and physical relationships among Earth, sun, moon and the solar system" (p. 114).

4. Pickwick (1997) researched the core concepts in Earth science and astronomy identified in the science curricula for UK and designed cross-curricular activities (see Department for Education and the Welsh Office, 1995; Scottish Office Education Department, 1993). He and his team (The Association for Astronomy Education: AAE) produced a series of activities 'Earth and beyond' aimed at meeting the requirements of the National Curriculum in England and Wales and the 5-14 Guidelines [now being superseded by a Curriculum for Excellence] in Scotland in response to needs expressed by teachers (particularly those in primary schools) for support to teach astronomy. A second book 'Earth and Space' was produced by the AAE group to meet the needs of secondary schools and promote astronomy education.

5. The astronomy and Earth science curricula; and teaching resources of China and New Zealand were compared and were found to be very similar (details available from authors). However, twice as much time was allocated to astronomy and Earth science topics at middle/high school level in China (32 hours over 4 years) compared to New Zealand (16 hours over 1-2 years). Thus, there is variation in the amount of attention paid by curriculum designers and school teachers to the teaching of astronomy in different countries of the world.

Socio-cultural factors influencing the acquisition of knowledge and conceptual skill

Social and cultural factors (for example, cultural tradition, access to education, and school

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attendance) are known to mediate the creation of a scientific world view (see Authors, 2006a). The current studies have identified several new factors (of particular relevance to these studies in China and New Zealand), including (a) China's one-child policy: *du sheng zi nü zheng si* in colloquial Mandarin or *putongwha*, (b) the priority given to science in China, (c) the incentive of competition for access to higher learning as a result of China's high population putting great pressure on limited resources, and (d) the emphasis given to astronomy and Earth science within the science curriculum.

In a recent article on psychology in China in *The Psychologist*, Han and Zhang (2007) report that research on "only children (resulting from the one-child policy)…found that only-children had superior cognitive abilities…compared to children with siblings" (p. 735). They cite the work of Jing, Wan, Lin, Ji, Jiao, and Fan (2003) who found that social factors such as improved educational opportunities as young people for those who are now parents had a follow-on effect to children in China today: "… the higher the educational status of the parents, the stronger the learning motivation of their only child" and "parent's high expectations of their child have (a) positive effect on the cognitive development of the only child" (p. 181). However, entry to higher education is intensely competitive, creating a social bottleneck metaphorically illustrated in colloquial Mandarin (*putongwha*) *pinyin* as *qian jun wan ma guo du mu qiao*, a military analogy: 'hundreds of thousands of troops are crossing the single log bridge'. This competition is considered to be the most important factor driving Chinese children to achieve: "In China parents pay much more attention to their children's education … because they have a very strong desire to make their children go to college…so that their children can get good jobs and lead a secure and wealthy life… Most Chinese families have only one child on whom the parents place their whole hope. So they make the children learn everything very well even from kindergarten" (T. Li, *personal communication,* 11 December 2007; see also Jing, 2006).

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The empirical research

In the light of this previous research, the current studies thus had three main aims:

(1) To illuminate competing theories on 'conceptual coherence' versus 'knowledge-in-pieces' by providing an in-depth qualitative and quantitative analysis of data in the field of astronomy and Earth science education obtained from ethnographic, in-depth, multi-media, multi-modal, repeated interviews of young people of diverse ethnicity in two distinct cultures. The research sought to explore the differences between what is detectably coherent in the representational systems at any particular stage in a young person's development and the changes apparent during subsequent development.

(2) The study aimed to clarify questions about 'experience' and 'expertise' since exposure to questions may lead to enhanced conceptual skill enabling more connections between concepts which should manifest as significant differences between Survey and Control Groups (see Cromer, 1987; Kuhl, 2000; Murphy and Medin, 1985).

(3) The investigation also aimed to explore 'knowledge-skill compounding' whereby improved conceptual skill may be effected by a complex interaction of socio-cultural factors including cultural awareness, priority given to science in society, and emphasis on astronomy in the science curriculum.

Our earlier work (Authors, 2006a, 2006b, 2007) reported aspects of the nature and development of astronomical concepts in young people from New Zealand and China at 2, 3 and 5-year intervals (in 1987, 1989, 1993 and 1998 in NZ; and 1994 and 2000 in China) with Control Groups in NZ in 1998 and in China in 2000. The current studies followed the same group of young people (those who were accessible) for a further period of 5 years to investigate more advanced astronomical knowledge with a final interview of Survey and Control Groups in 2003 (NZ) and 2004 (China). Thus the Survey Groups were interviewed at least three times (one participant five times between age 6 and age 22 spanning a period of 16

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years); and the Control Groups were interviewed twice. Utilising data from Piagetian interviews (see Appendix A), participants' concepts could be categorized using ordinal scales, and statistical correlations and concept category means determined to permit comparisons of subjects' expressions of their thinking through different media. This was done longitudinally from survey to survey, and in each culture (country), as explained below. By way of illustration, the ordinal descriptors for seasons and eclipses are shown in Figure 1.

Insert Figure 1 about here

Research questions

Interpretation of the complete longitudinal data against the backdrop of conflicting arguments in the literature over the nature of knowledge raised five research questions as follows:

1. Can evidence of conceptual coherence be detected as patterns of high correlation of representation utilising robust statistical analysis of multi-media qualitative data from clinical interviews categorized into ordinal format?

Coherence should show as patterns of high correlation in statistical tests (*Spearman rank correlation* [r_s]) between several media (Interview Verbal Responses, Drawing, Play-Dough) when representing a range of cosmological concepts, e.g., Earth Shape. Thus, for example, a child's description of roundness of the Earth or its likeness to an apple's shape should correspond to his/her drawings of circular shapes and moulding of play-dough into a ball.

2. Similarly, can robust quantitative analysis detect conceptual coherence as patterns of consistency of representation?

Coherence should be apparent as patterns of consistency of representation of concepts across media; i.e., concept category means derived from statistical tests (*Kolmogorov-Smirnov Two Sample Test* [*K-S*][1]) should be similar). That is, there should not be significant differences between young people's representations of concepts, however they are conveyed.

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Note. [1] *The K-S Test* is sensitive not only to differences of means and average ranks, but also to differences in the general shapes of the distributions such as dispersion and skewness (see Siegal and Castellan (1988). If there is no significant difference between the Groups then the *K-S Test* will result in a *p*-value of $p > .10$ or $p < .10$. If there is a significant difference than the *K-S Test* will result in a p-value of $p < .05$ or $p < .025$, or $p < .01$ with increasing degree of significance (M. Coates, personal communication, 25 July 2006).

3. Is there evidence that participants in longitudinal repeated measures designs develop conceptual skill in the domain under investigation as a result of linguistic experience?

Enhanced conceptual understanding and skill through repeated interviews across longitudinal surveys should result in Survey Groups having higher conceptual ability than Control Groups. Though not evident in our previous research (incorporating control groups) where 5 years was the interval between surveys, it might be expected after a 10-year interval, when individuals have more skill in making connections and combining concepts akin to experts as a direct result of being more aware of astronomical concepts through interviews. This 'repeated measures experience' should generate more advanced representation of concepts (apparent as greater category means) [*Kolmogorov-Smirnov Two-Sample Test: K-S*: alpha level 0.05] with greater differentiation between Survey and Control Groups in both cultures with increasing conceptual complexity.

4. Is multi-modal representation of cosmological concepts universal across cultures?

In our earlier research (see Authors, 2006a, 2006b, 2007) we found no significant differences [*K-S*: alpha level 0.05] between the cultures (New Zealand and China) and their associated ethnic groups (NZ European, NZ Maori, Samoan, Cook Island Maori, Han, Hui, Man, Chao etc.) in the multi-modal representation of basic static cosmological concepts.

5. Does conceptual skill from repeated measures combined with knowledge from learning and instruction afford improved understanding through 'knowledge-skill compounding'?

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Improved understanding of more complex dynamic astronomical phenomena (e.g., seasons and eclipses) through 'knowledge-skill compounding' should result in Survey and/or Control Groups in one culture (China) having higher conceptual ability than Survey and/or Control Groups in another culture (New Zealand) manifest as higher concept means [*K-S*: alpha level 0.05]. This heightened awareness may result from a combination of factors such as cultural tradition, access to education, curricular emphasis, social policy, and interpreter mediation, given the comparisons evident from the cross-cultural literature explored earlier.

Method

Sample and Surveys

The overall sample was composed of 345 young people (from the original 686 young people from New Zealand and China) who were available to participate in the cross-cultural longitudinal study (166 from New Zealand, including 75 males and 91 females; and 179 from China, including 96 males and 83 females); ages ranging from 2-12 years at the start of the study to 13-24 years at the end. Of these, 172 young people (83 from New Zealand and 89 from China); identified as the Main Survey Group; were interviewed in 1993 in New Zealand (1st NZ Survey) and in 1994 in China (1st China Survey). The same Survey Groups were interviewed again in 1998 in New Zealand (2nd NZ Survey) and in 2000 in China (2nd China Survey); together with their Control Group*s* (also of 172 young people); identified as the Main Control Group. Of these, 64 young people (34 from New Zealand and 30 from China); identified as the Extended Survey Group were accessible for a third interview in 2003 in New Zealand (3rd NZ Survey) and in 2004 in China (3rd China Survey); together with a balanced selection of those members of the Control Group (also of 64 young people); identified as the Extended Control Group; who were available. The New Zealand Survey Group included four youngsters from the initial studies in 1987-1989. The drop in numbers throughout the

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repeated interviews is a feature of longitudinal studies and is attributable to participants leaving their original homes, schools and communities for further education or employment.

Note. The results reported here are based on data of the Extended Survey Group and Extended Control Group from the 1st, 2nd and 3rd Surveys in New Zealand and China.

Longitudinal ethnographic continuity

In New Zealand, contact was maintained with participants through local schools and teachers by fax and mail with a school Principal acting as facilitator when the researcher was in China. Similarly, when the researcher was not in China, contact between the researcher and interpreters was maintained by email, fax, mail and telephone with a Chinese Professor of English at the researcher's host university facilitating and providing expert opinion in cases of doubt when interpreting audio tapes, drawings and photos of play-dough models. Links with schools were maintained by interpreters keeping track of participants' through the school community particularly when students graduated from primary to middle school (eventually spreading from one primary school to over fifty middle schools and universities).

Instrument

The instrument was an interview guide designed to cover the syllabus of astronomy and Earth science topics common to children in New Zealand and China at each level (see Appendix A for an abridged version indicating the main topics and questions). To limit interpreter mediation whereby finer nuances of conceptual explanation are lost in translation (to the disadvantage of the China Groups when using verbal language) the instrument (interview guide) had three consecutive lines written in English, *hanzi* (Chinese characters), and *pinyin* (a romanised phonetic system for transliterating colloquial Chinese). These were composed in English by the first author and translated and transcribed by two Professors of English and Chinese in China. All of the interviews were taped for later translation by interpreters familiar with astronomical terminology in English and Mandarin.

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Interview technique

Initially, if possible, the child was interviewed in the school playground. For example, for Earth Motion a shadow stick (metre ruler) was used in sunshine, the child being asked to place a pencil so that the tip of the pencil was touching the ruler shadow. With kindergarten children, time was spent introducing the concepts of shadows and the motion of shadows using dolls. After observing the divergence of the ruler shadow, the child was asked a series of questions about the motion of the Sun, Earth, and Moon in that order. Care was taken not to look at the Sun but the Moon was observed when visible. In the drawing sessions, the child was asked to draw the Earth, Sun and Moon and to describe and draw their motion (if any) using coloured pens and A4 paper. In the play-dough modelling sessions, the child was asked to model their motion with their own play-dough models using a piece of play-dough about the size of a small apple or orange presented as a lump (to avoid influencing the outcome by imposing structure). Thus three sets of data were obtained from each child on their Earth Motion cosmology: interview, drawing, and play-dough modelling (the latter being photographed) for later triangulation analysis. Similar arrangements were carried out for Earth Shape and Habitation (see authors 2006a and 2006b), Seasons and Eclipses.

Duration of interviews

Each interview session took between 40 and 120 minutes overall depending on the age of the child, there being four distinct sections of approximately equal duration, these dealing with different aspects and ensuring that the modalities were explored separately. For a 2-4 year-old child at Kindergarten each session might last 10-15 minutes (taking account of their more limited attention span) making 40-60 minutes in all. For a 10-12-year-old child at Primary School each session might last 20-30 minutes making 80-120 minutes in all. Generally, older children required less time. And young adults could complete the interview in a class period (40 – 60 minutes).

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Avoidance of cultural models

The separate sessions involving interviews, drawings and play-dough modelling activities with were all concerned with young people's representations in response to questioning, that is to say, models of Earth shape were not introduced to clarify responses (see authors, 2006b).

Inter-conceptual structure of astronomical and Earth science ideas

The multi-media, multi-modal methodology enabled young people to express a wide range of conceptual ideas in astronomy and Earth science ranging from the shape of the Earth, Sun and Moon as separate entities; properties like permanence, solidity and motion (see Spelke, 1991); phenomena like sky and gravity as an up/down gradient; these in turn relating to the motion of the Earth (a mini-theory in the language of Rips, 1995) and to the Earth-Sun-Moon system; eventually to complex dynamic ideas like day-and-night, seasons and eclipses (all macro-theories in the language of Murphy and Medin, 1985). A hierarchical representation of the astronomy concepts concerned is shown in Figure 2. This kind of inter-conceptual structure is described by Murphy and Medin (1985) as a "Network formed by causal and explanatory links, as well as sharing of properties picked out as relevant" (p. 298). It models semantic memory which is widely interpreted as being organised taxonomically with related hierarchies of categories increasing in complexity through subordinate, basic and superordinate levels with an underlying relationship between levels based on conceptual similarity (See Barsalou, 2003; Medin, 1989; Murphy & Lassaline, 1997). It also reflects the hierarchy used by Rollins, Denton and Janke (1983) in their analyses of Earth science concepts, and their description of conceptual levels of increasing coherence.

Multi-modal representation of conceptual elements in response to interview questions

Similarly, young people's representation of cosmological concepts stimulated by the research interview may also be visualised as a taxonomy with hierarchies of relationships between the media and sensory modalities used, and the modal skills (c.f. Barsalou, 2003).

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For example, Figures 3 and 4 set out the networks for the representations of 'Seasons of the year' and 'Eclipses' respectively, these diagrams giving the detail of the representing media, modalities and modal skills concerned with the represented objects and their properties. Media of representation and their associated modalities are triggered by the kind of probing used by the interviewer. If a verbal response is implied, the process might call for (1) description with recall from memory (say of the Earth during the four seasons of the year, or how eclipses come about). The answers may involve 'generative description' (say in response to questions like: 'Tell me about spring?' or 'Tell me about eclipses?'); (2) reasoning with recall (say in response to questions like: 'How long is each season?' or 'What causes eclipses?'); (3) reasoning with recall and sequencing may be invoked by questions like: 'What season comes after this?'; (4) reciting may result from being asked: 'Have you seen an eclipse?'; (5) analogy may be invoked by questions like: 'What is the shape of the Earth like?'. Or, (6) decentred imagination (see Donaldson, 1978) may be triggered by questions involving changes in the perspective of the observer or seeing things from another person's point of view, as in the question: 'What season would it be where your friend lives (on the other side of the Earth)'? 'What shape would the Earth be (look like) from the Moon?'.

Similarly, if the researcher invited the use of drawing, the question and response would activate sensory modalities in addition to those for verbal language, to enable, say, the conceptual-modal skill of drawing (with coloured felt pens on paper) the Earth and Sun to explain the seasons; or drawing the Earth, Sun and Moon to explain solar and lunar eclipses. Likewise, if the researcher indicated play-dough, the question and response would activate the tactile sensory modality in addition to those activated for drawing, e.g., modelling the shape of the Earth, Sun and Moon; or the motion of the Earth to show seasons; or the motion of the Earth and Moon for an eclipse (using their own models in the latter two cases).

Insert Figures 2, 3 and 4 about here

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Coding

The coding and categorisation scheme[1] was essentially similar to that reported previously (see Authors, 2006a, 2006b) with the addition of two new classification schemes for Seasons and Eclipses (see Figure 1). For the current studies the scheme was modified so that the ten cosmological conceptual elements measured (Earth Shape, Moon Shape, Sun Shape, Earth Motion, Moon Motion, Sun Motion, Daytime and Night-time, Seasons, Eclipses and Gravity) were each classified on a ten point scale (1-10) to afford more precise statistical analysis. Initial coding was done by the first author who conducted the interviews assisted by interpreters in China. The coding scheme of Seasons and Eclipses was checked by two astronomy educators from Carter National Observatory, Wellington. Two exemplars for each category of the two conceptual elements in each culture in the three media; and their associated representing modalities were selected. These represented 31 % of the data in each concept in each media there being 10 categories per concept, two exemplars per category, in two cultures, making 40 exemplars per concept with 128 participants. The results verified the categorisation scheme with intercoder agreement of 85 to 95%; *Cohen's kappa* $\kappa = .83$ to .94.

Note. [1] By *coding and categorisation scheme* we mean a system of schema for classifying participants' cosmological concepts (e.g., eclipses, seasons) on ordinal scales from least to most scientific to afford statistical analysis. The scheme was based on descriptors and thumb-nail sketches encapsulating the essential features of each concept, represented through a variety of media, and readily understood by coders (see Bayerl, Lüngen, Gut & Paul, 2003). Similar classification schemes have been used extensively in the field (see Nussbaum & Novak, 1976; Nussbaum, 1979; Sneider & Pulos, 1993; Vosniadou & Brewer, 1992, 1994).

Results and Discussion

Note: Individual identities have been disguised in the names used in the following section.

Exemplars of Categories of Dynamic Cosmological Concepts: Seasons

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Conceptual coherence in multi-modal representations

Typical responses to the researcher's main question: *What causes the seasons of the year?* were as follows (referring to the categories in Figure1):-
A category 2 response from the interview with Kong Yuan Yuan (Chinese Female, 16 years, 7 months in the main survey) was *The seasons are caused by the changes of temperature.* In the drawing section of the interview she drew symbolic seasons in quadrants.

Keegan (New Zealand Maori, 14 years, 1 month, also in the main Survey) gave a category 5 response to the same question: *The Sun doesn't rotate but the Earth does…and it's on its axis…and it rotates…and that causes the seasons.* Keegan later drew the Earth spinning on a tilted axis in a single position with the Sun's rays shining on the Earth. He did not name the seasons or give their sequence.

In the case of Liu Tian Yi (Chinese Male of the Manchurian minority group, 17 years, 0 months in the main Survey) his response was placed in category 6: *The changes of the distance of (between) the Earth and Sun…Spring, Summer, Autumn, Winter.* He later drew the Earth in four positions with seasons. He indicated the Earth spinning on a tilted axis. Earlier he had said that the Earth rotated and revolved around the Sun.

A category 8 response was given by Tanya (New Zealand, European Female, 13 years, 7 months in the main Survey): *The axis that is closer to the Sun is summer.*
Researcher: *You talked about the Earth being tilted on its axis?*
Tanya: *It's tilted on its axis…I think that it's when the top part of the Earth is tilted towards the Sun that its summer…and the other one is winter.*
Later, Tanya drew a single Earth tilted on its axis with the Northern Hemisphere inclined towards the Sun and labelled as Summer; and the opposite position in the Southern hemisphere labelled as Winter. The intermediate positions were labelled as Spring and Autumn respectively. Earlier Tanya had said that the Earth rotated and revolved around the Sun.

Alice's (NZ European Female, 14 years, 3 months in the Control group) category 9 drawing is shown below in Figure 5a. Li Hong Gang's (Chinese Male, 16 years, 3 months in the Main survey) category 10 model is shown below in Figure 5b.

Insert Figures 5a and 5b about here

A category 10 response was given by Jin Dao (Chinese Female of the Chao (Korean) minority group, 21 years, 7 months in the main survey: *There is an angle when the Earth revolves around the Sun, so the direct shining point of the Sun onto the Earth could change (changes). For instance, (when) the Sun shines directly on the equator, we have Spring in the Northern Hemisphere on March 21st. On July 22nd, the Sun shines directly on the Tropic of Cancer (and) it is Summer in the Northern Hemisphere. On September 22nd, the Sun shines directly on the equator and we (in China) are in Autumn. When the Sun shines directly on the Tropic of Capricorn the Northern Hemisphere is in Winter.*
Later, Jin Dao drew four seasonal quadrants with details of the position of the Sun with respect to the Earth and with reference to the tropics and the equator as in her explanation.

Exemplars of Categories of Dynamic Cosmological Concepts: Eclipses

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Conceptual coherence in multi-modal representations

Typical responses to the researcher's main question: *What causes eclipses?* were as follows (see Figure 1):-

A category 4 response was given by Anthony (NZ Euro-Samoan Male, 14 years, 10 months in the Control group): *When the Earth, Sun and Moon meet up, the Moon blocks the Sun's rays (Solar eclipse)*. Later, Anthony drew a Solar eclipse correctly with light rays and shadow cone but called it a Lunar eclipse. His Solar eclipse showed nine planets aligned with the Sun.

Jessica's (NZ Maori Female, 16 years, 4 months in the Control group) response was placed in category 6: *A Lunar eclipse is when the Moon goes in front of the Sun. A Solar eclipse is when the planets block out the Sun's rays.* In her drawing Jessica also confused Lunar and Solar eclipses by reversing their names.

In the case of Weng Jia Qi (Chinese Male, 13 years, 5 months in the Control group) his response was placed in category 7: *(A) Solar eclipse is when the Sun, Moon and Earth are in a line. (A) Lunar eclipse is when the Sun, Earth and Moon are in a line.* Later Weng Jia Qi drew his Solar eclipse with light rays from the Sun touching the Moon and Earth; but in his Lunar eclipse he only had light rays from the Sun to the Moon.

Xiao Yang's (Chinese Male, 17 years, 11 months in the Main Survey) category 8 drawing of Solar and Lunar eclipses with rays and shadow cones is shown in Figure 6a. Robin's (NZ European Male, 16 years, 8 months in the Reserve group) category 10 drawing of his Solar eclipse is shown in Figure 6b.

Insert Figure 6a and 6b about here

A category 9 response was given by Haley (NZ European, 21 years, 11 months in the Main survey): W*hen the Moon passes directly between the Sun and the Earth it hides the Sun: this is called a Solar eclipse. In an eclipse of the Moon, the Moon passes into the Earth's shadow.* Later, Haley drew Solar and Lunar eclipses with light rays from the Sun and shadow cones.

Zhao Jing Hong (Chinese: Manchurian) Female, 18 years, 1 month in the Control group) gave a category 10 response: *A Solar eclipse is when the Moon, Earth and Sun are in a line. If the sunlight that shines on the Earth is fully covered by the Moon, it is a total Solar eclipse; if partly, a partial Solar eclipse. A Lunar eclipse is when the Moon, Earth and Sun are in a line, the Moon moves to the umbra area of the Earth (total shadow). If the sunlight can't reflect (shine) on to the Moon fully, it forms a total Lunar eclipse; if partly, a partial lunar eclipse.* Zhao Jing Hong drew both Solar and Lunar eclipses in with rays and shadow cones.

Statistical results and significance levels

The results supported the strategies used to answer the five research questions as follows:

1. There was evidence of conceptual coherence in the Survey Groups of both cultures (China and New Zealand) manifest as patterns of high correlation between media of representation and their associated representing and represented modalities: *Spearman* $r_s > .50$; $p < .001$.

That is, whichever way the subjects represented their concepts, the category to which their

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concepts could be ascribed closely corresponded. The statistical detail of the high inter-correlations between the media is given in Appendix B1.

2. There was also affirmation of conceptual coherence as consistency of representation of cosmological concepts across media and their associated modalities. The Difference of Means between Media [*ΔMM*] within groups was less than one Cosmological Concept Category: *K-S:* $p > .10$ or $p < .10$ at an alpha level of 0.05. The statistical detail of the means and the differences for *basic static* concepts (Earth Shape), for *basic dynamic* concepts (Earth Motion), and for *complex dynamic concepts* (Seasons) are given in Appendix B2, and are illustrated in Figures 7 – 9 below.

Insert Figures 7, 8 and 9 about here

3. The results also confirmed that participants in longitudinal repeated measures designs can develop enhanced conceptual understanding and skill over control groups with less exposure. This was manifest as higher Cosmological Category Means *within* Media of Representation *between* Groups [*ΔMG*]; i.e., in this case in Survey Groups over Control Groups in both cultures: *K-S:* $p > .10$ or $p < .10$ at an alpha level of 0.05. Appendix B3 provides the statistical detail showing that for *static* cosmological concepts (like Moon Shape); *basic dynamic* concepts (like Sun Motion); and *complex dynamic* concepts (like Gravity) the Survey Groups had higher cosmological concept category means in all but one area.

4. The question of whether multi-modal representation of cosmological concepts is universal across cultures was also illuminated by the results which supported our earlier findings; there being no significant differences between the New Zealand and China groups in representation of basic static cosmological concepts. The China Survey Group had higher Concept Category Means than the NZ Survey Group in 15 of 27 cases (3 Media x 3 Measures x 3 Concepts). The China Control Group had higher Concept Category Means than the NZ Control Group in

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14 of 27 cases: *K-S:* $p > .10$ or $p < .10$ at an alpha level of 0.05: Appendix B4 contains the statistical detail for Earth Shape.

5. The final question of whether conceptual skill from repeated measures combined with knowledge from learning and instruction afford improved understanding was also clarified with evidence of improved understanding through 'knowledge-skill compounding' to the advantage of the China Groups. The China Survey Group had higher Concept Category Means than the NZ Survey Group in 30 of 39 cases; the China Control Group had higher Concept Category Means in 33 of 39 cases: *K-S:* $p > .10$ or $p < .10$ at an alpha level of 0.05. Appendix B5 provides the statistical detail for the differences between samples in Moon Motion, Sun Motion and Eclipses (with eclipses illustrated in Figure 10).

Insert Figure 10 about here

Summary of results

To a substantial degree, the results have supported the thinking outlined for each of the research questions. There was strong evidence of conceptual coherence as patterns of high correlation of cosmological concept categories *between* media of representation in all three types of concepts: basic static, basic dynamic, and complex dynamic. Similarly, there were persuasive indications of conceptual coherence in the form of patterns of consistency of cosmological concept categories *across* the media of representation in all three concept types. The searches for evidence of both forms of conceptual coherence (correlation and consistency) were made within Surveys (over relatively short periods of time); rather than across Surveys (longitudinally) to avoid confounding from changes due to development which we have reported (see Authors, 2006b).

There was also cogent confirmation of enhanced conceptual understanding and conceptual skill in Survey Groups over Control Groups in the form of higher cosmological category means between the Groups across the media of representation. In keeping with our earlier

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findings (see Authors 2006a, 2006b, 2007) the results indicated that there was little difference between the two cultural groups in basic static cosmological concepts, e.g., Earth Shape.

However, in the case of both basic dynamic and complex dynamic cosmological concepts, there was evidence of improved understanding by China Groups over NZ Groups through 'knowledge-skill compounding', arguably influenced by cultural, educational and social factors, taking into account the socio-cultural literature reviewed earlier. These differences between Groups initially became apparent in basic dynamic cosmological concepts requiring dynamic integration of related concepts to form mini-theories, such as Moon Motion and Sun Motion; the China Control Group having more advanced concepts than the NZ Control Group. And the differences became more significant with conceptual complexity during the assimilation of complex dynamic concepts to create macro-theories; where both China Groups had a better understanding of Eclipses than the NZ Groups. This suggests subtle socio-cultural factors at play, such as cultural tradition, priority given to science education, curricular emphasis, and social policy, to the advantage of the China Survey Group, and, to a lesser extent, the China Control Group over the NZ Groups.

Despite considerable effort to limit interpreter mediation, which might act to the advantage of NZ Groups, who were being interviewed in their native language, it was found that the greatest differences between cultures (*K-S*: Moon Motion, $p > .025$; Sun Motion, $p < .01$; Eclipses, $p < .025$) were in the culturally neutral media of Drawing and Play-Dough where the China Groups were less dependent on language (see Figure 10: Eclipses). This suggests that interpreter mediation may have masked nuances of verbal explanations. The results confirmed that play-dough is the most effective media for communicating complex dynamic concepts such as eclipses, followed by drawing, then verbal language.

These socio-cultural effects may have been latent in earlier studies but only became manifest and statistically significant in the final 3rd Survey. The cultural similarity between

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Conceptual coherence in multi-modal representations

Survey Groups may be explained by the NZ Survey Group being able to compensate for socio-cultural factors such as differences in curriculum emphasis by enhanced conceptual understanding and skill acquired through repeated measures so that they were not as disadvantaged as their controls (see Research question 3).

The general pattern was one of similarity between Groups and Cultures. This suggests that the enhanced understanding of dynamic concepts shown by Chinese students in Moon Motion, Sun Motion, and Eclipses is not universal across *all* dynamic concepts but is limited to associations between dynamic concepts. And this can be explained by differences in social policy (e.g., the reported intellectual advantage of only children over children with siblings in modern China, coupled with the related high expectation of teachers and parents, and fierce competition for places in high status universities); together with curricular emphasis (e.g., the advantage of more time being allocated to astronomy) in the case of China Groups; and experience/conceptual skill in both China and NZ Survey Groups (see Barsalou, 2003).

Conclusion

Evidence in support of conceptual coherence rather than fragmented knowledge-in-pieces

The current research has found evidence of conceptual coherence in mental development and associated modalities within the research paradigm of children's cosmologies. The findings are compatible with both a representational connotation and a cognitive skill interpretation of concepts (hence our use of the term 'knowledge-skill compounding' above). Although the idea of dispensing with *representation* altogether may appeal to some dynamic theorists, such a course of action would not be conducive to further research in this field. Conducting the "sustained empirical research in cognitive science" to seek evidence that "cognitive systems may well be dynamical systems" which van Gelder (1998) advocates (p. 615) with children without representation of some form or another would be problematical. We have argued (see Authors, 2006b) that creating a concept may be analogous to the

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collapse of a wave function as in quantum theory; so that concepts may not be stored as representations, but rather as recipes or formulae for their re-creation; but we stopped short of the idea that representations are redundant for the good reason that children claim to be able to visualise celestial objects such as the Earth, Sun and Moon; and to be capable of manipulating these objects mentally. Even very young children, around age 3 and 4, claim to be able to imagine falling leaves in autumn and falling snow in winter when describing and drawing the seasons. The evidence from current studies suggests that conflicting theories of cognition are *metaphors* which share elements of both representational and non-representational systems depending on the mode of enquiry (analogous to wave-particle dualism in quantum mechanics, to make another comparison with physical science). They may reflect a deeper semantic process akin to Piaget's 'reflective abstraction' which creates conceptual coherence, enabling us to make sense of the world (see Donaldson, 1978). From this perspective, conceptual coherence may be seen to be an integral characteristic of cognition which humans exhibit from an early age through theory-like constructions of the world. However, although conceptual coherence is a characteristic of scientific theories this is not to say that children's theories are "scientific" in the traditional sense. Rather they are seen to be embryonic scientific theories not unlike early theories in the history of science (see Kuhn, 1962) in that they include intuitive, cultural and scientific strands. These become more scientific with development and learning within an environment where science is nurtured such as a modern kindergarten, school, college or university, where, in the main, teachers hold a scientific world-view. Nevertheless they exhibit conceptual coherence manifest as concept reproductive skill - an ability to consistently represent a concept (such as the Earth's shape) in a variety of modalities and through a range of media (such as verbal description, drawing, and play-dough modelling). Murphy and Medin (1985) also recognised that early concepts are interrelated with early theories: "Although young children may not have

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scientific theories or sophisticated schemata, they may well use their understanding of the world, or proto-theories, in forming concepts" (p. 311). Clearly such knowledge as young people have cannot be "in-pieces" since, if it were, cognition would also be incoherent (see Donaldson, 1976). Evidence of fragmentation may reflect some researchers' time-restricted methods which operate with limited questions and minimal probing, resulting in impoverished data lacking the richness of more open-ended, time-generous approaches (see Agan & Sneider, 2004). Our own research involving in-depth, multi-media interviews certainly ties in with Barsalou's idea of a concept as a skill and, with it, the notion of conceptual coherence as an ability to consistently create more or less identical concepts using different media of representation involving different sensory modalities.

Recommendations for further research

We believe that more cross-cultural research is needed to produce data and evidence which should further confirm views in the coherence versus knowledge-in-pieces debate and on the issue of concepts as representations and/or skills. These investigations should focus on fields such as children's cosmologies for, as Murphy and Medin (1985) surmised some time ago, "The study of children's concepts and semantic development may be a crucial area for showing the importance of theories in conceptual structure" (p. 308). The conceptual elements, structures and processes that we are investigating are by their very nature tenuous and require perceptive, fine-tuned methodologies to reveal their composition. We owe it to young people to provide optimum learning environments and we can only do so by finding out what they already know and how they learn by rigorous yet sensitive research.

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Appendix A: Interview Guide (Abridged)

Motion Study
1. Does the Earth move?
2. Does the Sun move?
3. Does the Moon move?
4. ***Draw how the Earth, Sun and Moon move*** (on your Motion Drawing).

Time Study
1. What is a year?
2. Does a year have anything to do with the Earth?
3. Does a year have anything to do with the Sun?
4. Does a year have anything to do with the Moon?
5. What is a month?
6. Does a month have anything to do with the Earth?
7. Does a month have anything to do with the Sun?
8. Does a month have anything to do with the Moon?
9. What is a day?
10. Does a day have anything to do with the Earth?
11. Does a day have anything to do with the Sun?
12. Does a day have anything to do with the Moon?

Daytime and Night-time
1. What is daytime?
2. What happens to the Earth in daytime?
3. What happens to the Sun in daytime?
4. What happens to the Moon in daytime?
5. What is night-time?
6. What happens to the Earth at night-time?
7. What happens to the Sun at night-time?
8. What happens to the Moon at night time?
9. ***Draw the Earth, Sun and Moon at daytime and night-time*** (on your Time Drawing).

Shape Study
Earth Shape
1. Tell me about the Earth?
2. What shape is the Earth?
3. What is the shape of the Earth like? Like a ...
4. ***Draw the Earth*** (on your Shape Drawing).
5. ***Make the shape of the Earth with green play dough.***
6. What shape is your model of the Earth?

Ground & Sky
1. Tell me about the ground?
2. What shape is the ground?
4. ***Draw the ground*** (on your Shape Drawing)..
5. What shape is your drawing of the ground?
6. Tell me about the sky?
7. What shape is the sky?
8. ***Draw the sky*** (on your Shape Drawing).
9. What shape is your drawing of the sky?

Sun Shape
1. Tell me about the Sun?
2. What shape is the Sun?
3. What is the shape of the Sun like? Like a ...
4. ***Draw the Sun*** (on your Shape Drawing).
5. ***Make the shape of the Sun with red play dough.***
6. What shape is your model of the Sun?

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Moon Shape

1. Tell me about the Moon?
2. What shape is the Moon?
3. Is the Moon always the same shape?
4. If the Moon appears to change shape, why does it appear to change shape?
5. What is the shape of the Moon like? Like a ...
6. ***Draw the Moon*** (on your Shape Drawing).
7. ***Make the shape of the Moon with yellow play dough.***
8. What shape is your model of the Moon?
9. What would the Earth look like from the Moon?

Habitation, Identity & Gravity Study

1. ***Draw yourself*** (on your Shape Drawing).
2. Where did you draw yourself?
3. What are you standing on?
4. How are you able to stand there?
5. ***Draw a friend who lives a long way away from you – as far away as you can imagine.***
6. Where did you draw your friend?
7. What is your friend standing on?
8. How is your friend able to stand there?
9. Imagine that you dropped a ball into a very deep well-hole. What would happen to the ball?
10. ***Draw the well-hole, yourself, and the ball.***

Seasons Study

1. Tell me about the seasons?
2. What causes the seasons?
3. What are the names of the seasons?
4. Tell me about Winter?
5. Tell me about Spring?
6. Tell me about Summer?
7. Tell me about Autumn?
8. How long is each season?
9. Why do the seasons change?
10. What season is it now?
11. What was the season before this?
12. What season comes after this?
13. Do different places on Earth have different seasons?
14. Why do different places have different seasons?
15. Thinking of your friend who lives in China (New Zealand) on the other side of the Earth: What season would it be where your friend is?
16. Do the seasons have anything to do with the Earth?
17. Why do the seasons have something to do with the Earth?
18. Do the seasons have anything to do with the Sun?
19. Why do the seasons have something to do with the Sun?
20. Do the seasons have anything to do with the Moon?
21. Why do the seasons have something to do with the Moon?
22. ***Draw the Earth and Sun to explain the seasons***
23. ***Model the seasons with your play-dough models of the Earth and Sun.***

Eclipses Study

1. Do you know what eclipses are?
2. Tell me about eclipses?
3. Have you seen an eclipse?
4. What causes eclipses?
5. ***Draw the Earth, Sun and Moon to explain eclipses.***
6. ***Model eclipses with your play-dough models of the Earth, Sun and Moon.***

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Appendix B1

Statistical detail for Research Question 1

For *static* cosmological concepts (Earth Shape, Moon Shape, Sun Shape), there was little difference between the correlations: e.g., Earth Shape:

Survey	***Interview v Drawing***	***Interview v Play-Dough***	***Drawing v Play-Dough***
	r_s	r_s	r_s
3rd NZ	.68	.82	.72
3rd China	.74	.67	.89

However with *basic dynamic* cosmological concepts (Earth Motion, Moon Motion, Sun Motion) differences showed (indicated *) in the 3rd Survey in the case of the motion of the Moon and Sun, the China Survey Group being better able to describe their concepts using a combination of play-dough and verbal language; e.g., Moon Motion:

Survey	***Interview v Drawing***	***Interview v Play-Dough***	***Drawing v Play-Dough***
	r_s	r_s	r_s
3rd NZ	.60	.61	.59
3rd China	.60	.81*	.58

In the case of *complex dynamic* concepts (Day/Night, Seasons, Eclipses, Gravity), the plateaux effect tended to accentuate r_s values (indicated *) when most participants held the scientific view or close to it (cosmological concept categories 9 & 10) e.g., Day/Night:

Survey	***Interview v Drawing***	***Interview v Play-Dough***	***Drawing v Play-Dough***
	r_s	r_s	r_s
3rd NZ	.79	.83	.96*
3rd China	.91	.88	.95*

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Appendix B2
Statistical detail for Research Question 2.
Conceptual coherence as consistency of representation.

For the *static* cosmological concept Earth Shape (see Figure 7), the means and the differences were:

Survey	***Interview***	***Drawing***	***Play-Dough***	***Difference in Means***
	M	*M*	*M*	*ΔMM*
1st NZ	5.52	5.48	6.32	0.80
2nd NZ	8.53	8.03	8.27	0.50
3rd NZ	9.82	9.41	9.62	0.41
1st China	6.03	5.97	6.73	0.78
2nd China	8.93	8.31	8.59	0.59
3rd China	9.97	9.57	9.73	0.40

For the *basic dynamic* cosmological concept Earth Motion (see Figure 8), the means and differences were:

Survey	***Interview***	***Drawing***	***Play-Dough***	***Difference in Means***
	M	*M*	*M*	*ΔMM*
1st NZ	6.35	5.58	5.87	0.77
2nd NZ	8.90	8.43	8.63	0.47
3rd NZ	9.74	9.71	9.85	0.14
1st China	6.90	6.10	6.67	0.80
2nd China	9.00	8.45	8.76	0.55
3rd China	9.70	9.67	9.90	0.23

Note. The combination of development and learning shows as a reduction in *ΔMM* over time.

For the c*omplex dynamic* cosmological concept Seasons (see Figure 9), the means and differences were:

Survey	***Interview***	***Drawing***	***Play-Dough***	***Difference in Means***
	M	*M*	*M*	*ΔMM*
3rd NZ	5.88	5.74	6.18	0.44
3rd China	6.10	6.00	6.43	0.43

Kolmogorov-Smirnov: $p > .10$ or $p < .10$ at an alpha-level of 0.05.

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Appendix B3
Statistical detail for Research Question 3.

Evidence of enhanced conceptual understanding and skill.

In the case of *static* cosmological concepts like Moon shape, the Survey Groups had higher cosmological concept category means in all but one case, e.g., Moon Shape:

Group	*Interview*	*Drawing*	*Play-Dough*
	M	*M*	*M*
3rd NZ Survey	8.35	8.12	8.21
3rd NZ Control	7.94	7.82	7.74
Difference in Means between Groups [ΔMG]	0.41	0.30	0.47
3rd China Survey	8.20	8.33	8.07
3rd China Control	7.93	7.77	7.67
Difference in Means between Groups [ΔMG]	0.27	0.56	0.40

A similar pattern was apparent in *basic dynamic* cosmological concepts, e.g., Sun Motion:

Group	*Interview*	*Drawing*	*Play-Dough*
	M	*M*	*M*
3rd NZ Survey	8.59	8.21	8.50
3rd NZ Control	8.35	7.94	8.06
Difference in Means between Groups [ΔMG]	0.24	0.27	0.44
3rd China Survey	8.93	8.63	9.00
3rd China Control	8.67	8.33	8.73
Difference in Means between Groups [ΔMG]	0.26	0.30	0.27

The results for *complex dynamic* concepts were similar: e.g., Gravity:

Group	*Interview*	*Drawing*	*Play-Dough*
	M	*M*	*M*
3rd NZ Survey	7.68	7.65	7.91
3rd NZ Control	6.85	6.68	6.91
Difference in Means between Groups [ΔMG]	0.83	0.97	1.00
3rd China Survey	7.97	7.83	8.07
3rd China Control	7.17	7.10	7.40
Difference in Means between Groups [ΔMG]	0.80	0.73	0.67

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Appendix B4
Statistical detail for Research Question 4.
Evidence of cultural similarity was apparent in basic static concepts, e.g. Earth Shape:

Group	*Interview*	*Drawing*	*Play-Dough*
	M	*M*	*M*
3rd NZ Survey	9.82	9.41	9.62
3rd China Survey	9.97	9.57	9.73
Difference in Means between Groups [ΔMG]	0.15	0.16	0.11
3rd NZ Control	9.71	9.26	9.44
3rd China Control	9.87	9.40	9.60
Difference in Means between Groups [ΔMG]	0.16	0.14	0.16

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Appendix B5
Statistical detail for Research Question 5.
Evidence of improved understanding through knowledge-skill compounding.

The general pattern of basic dynamic cosmological concepts was one of similarity. However, in the case of Moon Motion, differences appeared, e.g.:

Group	*Interview*	*Drawing*	*Play-Dough*
	M	*M*	*M*
3rd NZ Survey	9.21	8.94	9.09
3rd China Survey	9.17	8.80	9.37
Difference in Means between Groups [ΔMG]	0.04	0.14	0.28
3rd NZ Control	8.62	8.74	8.88
3rd China Control	8.90	8.63	9.17
Difference in Means between Groups [ΔMG]	0.28	0.11	0.29**

** *K-S*: $p < .025$: significant at an alpha-level of 0.05: reflecting Chinese students greater understanding of Moon's motion due to use of Lunar Calendar and curriculum emphasis.

Similarly, in the case of Sun Motion differences were apparent in the 3rd Survey, e.g.:

Group	*Interview*	*Drawing*	*Play-Dough*
	M	*M*	*M*
3rd NZ Survey	8.59	8.21	8.50
3rd China Survey	8.93	8.63	9.00
Difference in Means between Groups [ΔMG]	0.34	0.42	0.50
3rd NZ Control	8.35	7.94	8.06
3rd China Control	8.67	8.33	8.73
Difference in Means between Groups [ΔMG]	0.32	0.39*	0.67***

* *K-S*: $p < .05$; *** *K-S*: $p < .01$; at an alpha-level of 0.05: echoing Chinese students greater understanding of the Sun's rotation cycle and revolution around the centre of the Milky Way.

With complex dynamic concepts there was significant dissimilarity in Eclipses (see Figure 10):

Group	*Interview*	*Drawing*	*Play-Dough*
	M	*M*	*M*
3rd NZ Survey	4.59	4.94	4.97
3rd China Survey	6.20	6.47	6.53
Difference in Means between Groups [ΔMG]	1.61*	1.53**	1.56**
3rd NZ Control	4.32	4.44	4.68
3rd China Control	6.00	6.30	6.40
Difference in Means between Groups [ΔMG]	1.68*	1.86*	1.72*

**K-S*: $p < .05$; ** *K-S*: $p < .025$; at an alpha-level of 0.05.

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Figure 1. *Ordinal scale for* ***seasons***

Increase in scientific understanding

10. Seasons caused by tilt of the plane of the Earth's orbit to the plane of the equator. Drawings feature Tropics of Cancer and Capricorn on the Earth but may not name as such.
9. Seasons caused by tilt of the plane of the Earth's orbit to the plane of the equator. Knows sequence: Spring, Summer, Autumn, Winter (reversed in opposite hemisphere).
8. Seasons caused by the tilt of the plane of the Earth's orbit to the plane of the equator. Uncertain of sequence but knows that Summer and Winter are opposite positions.
7. Seasons caused by the tilt of the plane of the Earth's orbit to the plane of the equator. Mentions (interview) or indications (drawing) of rotation and revolution of Earth.
6. Seasons related to rotation of Earth and revolution of Earth around Sun. Unsure of significance of tilted axis; e.g. Seasons are caused by changes in the position of the Earth.
5. Seasons related to rotation of Earth on axis and/or revolution of Earth around Sun. Unsure of significance of tilted axis. May be uncertain of names of seasons or sequence; e.g., Earth coser to the Sun in Summer.
4. Seasons related to relative motion of Earth and/or Sun and/or Moon; e.g., seasons caused by Sun and/or Moon orbiting Earth, or by changes in distance between the Earth and the Sun.
3. Seasons related to relative motion of Earth and/or Sun and/or Moon in some way. Earth divided into seasonal sectors or quadrants (Earth may be assumed or virtual).
2. Knows main features of seasons but does not relate cause to motion of Earth, Sun or Moon.
1. Uncertain of cause of seasons.

Ordinal scale for ***eclipses***

Increase in scientific understanding

10. Knows and can name both Lunar and Solar eclipses. Explanation includes total and partial eclipses. Drawings include umbra and penumbra with dual sets of light rays from Sun and shadow cones (shaded or hatched) touching Earth and Moon.
9. Knows and can name both Lunar and Solar eclipses. Explanation covers only total eclipses. Drawings include umbra with single sets of light rays from Sun and single shadow cones.
8. Knows and can name both Lunar and Solar eclipses. Explanation covers only total eclipses. Drawings feature single sets of light rays from Sun touching Earth and Moon but no shading or hatching or labelling of shadow cones or umbra or penumbra.
7. Knows and can name both Lunar and Solar eclipses. Explanation incomplete; e.g. no light rays from Sun, but shadow cones, or no shadow cones but rays touching Earth and Moon.
6. Knows both Lunar and Solar eclipses but names reversed or uncertain. Explanation incomplete; e.g., no light rays from Sun but shadow cones, or no shadow cones but light rays.
5. Knows both Lunar and Solar eclipses but names may be reversed or uncertain. Can explain relative positions and relative motion of Earth, Moon and Sun but explanation incomplete.
4. Knows only Solar eclipse but may not name as such. Can explain relative positions and motion of Earth, Moon and Sun. Able to explain effect; e.g. "It gets dark on the Earth".
3. Knows only Lunar eclipse but may not name as such. Can explain relative positions and motion of Earth, Moon and Sun. Able to explain effect; e.g. “It gets dark on the Moon”.
2. Knows some detail of an eclipse but may not know name or uncertain. Explanations such as “Moon moves in front of the Sun”, “Moon covers the Sun and it is dark”, “It gets dark on the Moon”.
1. Uncertain of nature and/or cause of eclipses.

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Conceptual coherence revealed in multi-modal representation of astronomy knowledge

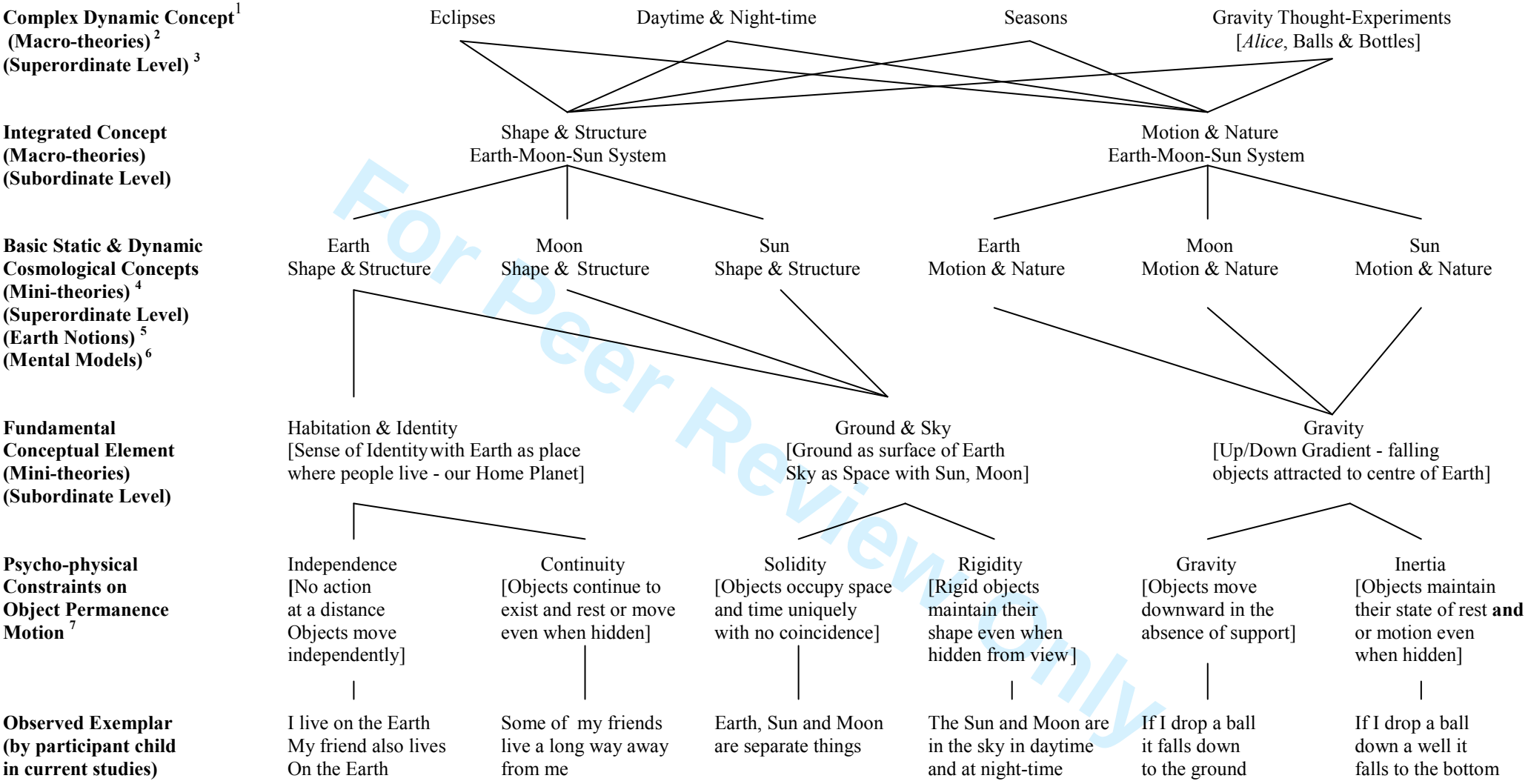

Figure 2. Hierarchical conceptual structure[1,2] of astronomical ideas showing exemplars, constraints, conceptual elements, mini-theories and macro-theories.

Note. [1]Murphy & Lassaline (1997). [2]Murphy & Medin (1985): "Network formed by causal and explanatory links, as well as sharing of properties picked out as relevant" (p. 298, Table 1).[3]Rollins, Denton & Janke (1983). [4]Rips (1995). [5]Nussbaum & Novak (1976). [6]Vosniadou & Brewer (1992). [7]Spelke (1991).

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Conceptual coherence revealed in multi-modal representation of astronomy knowledge

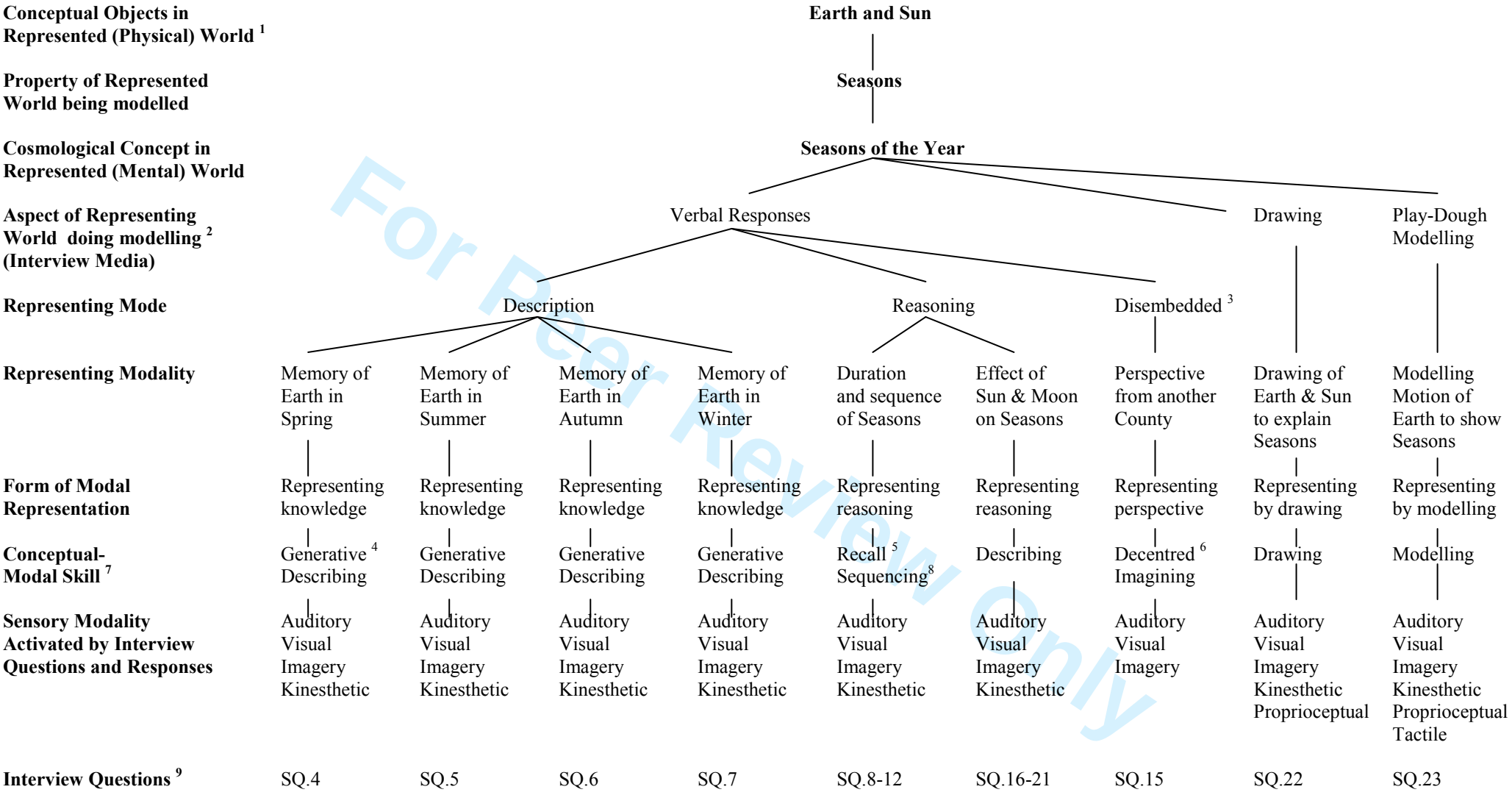

Figure 3. Network of representation of cosmological concept *Seasons of the Year* with detail of representing media, modalities, modal forms, and modal skills.

Note. [1]Murphy & Medin (1985). [2]Rumelhart & Norman (1983). [3,6]Donaldson (1978). [4]SQ5. *Tell me about Spring?* afforded generative responses. [5]SQ8. *How long is each season?* attuned recall from memory. [7]Barsalou (2003). [8]SQ12. *What season comes after this?* invited calculation. [9]Interview Protocol Questions.

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Conceptual coherence revealed in multi-modal representation of astronomy knowledge

Conceptual Objects in Represented (Physical) World [1]	**Earth, Sun and Moon**								
Property of Represented World being modelled	**Eclipses**								
Cosmological Concept in Represented (Mental) World	**Solar and Lunar Eclipses**								
Aspect of Representing World doing modelling [2] **(Interview Media)**	Verbal Responses					Drawing		Play-Dough Modelling	
Representing Mode	Description[3]		Reasoning[4]		Reciting[5]				
Representing Modality	Memory of cause of Solar Eclipse	Memory of cause of Lunar Eclipse	Effect of Moon Blocking Sun (Solar Eclipse)	Effect of Moon Blocking Sun (Lunar Eclipse)	Reciting Experience of Eclipses	Drawing Solar Eclipse	Drawing Lunar Eclipse	Modelling Solar Eclipse	Modelling Lunar Eclipse
Form of Modal Representation	Representing knowledge	Representing knowledge	Representing reasoning	Representing reasoning	Representing experience	Representing by drawing	Representing by drawing	Representing by modelling	Representing by modelling
Conceptual-Modal Skill [6]	Recall Describing	Recall Describing	Generative Describing	Generative Describing	Recall Imagining	Drawing	Drawing	Modelling	Modelling
Sensory Modality Activated by Interview Questions and Responses	Auditory Visual Imagery Kinesthetic	Auditory Visual Imagery Kinesthetic	Auditory Visual Imagery Kinesthetic	Auditory Visual Imagery Kinesthetic	Auditory Visual Imagery Kinesthetic	Auditory Visual Imagery Kinesthetic	Auditory Visual Imagery Kinesthetic	Auditory Visual Imagery Kinesthetic Proprioceptual	Auditory Visual Imagery Kinesthetic Proprioceptual Tactile
Interview Questions	EQ.1-4	EQ.1-4	EQ.2	EQ.2	EQ.3	EQ.5	EQ.5	EQ.6	EQ.6

Figure 4. Network of representation of cosmological concept *Eclipses* with detail of representing media, modalities, modal forms, and modal skills.

Note. [1]Murphy & Medin (1985). [2]Rumelhart & Norman (1983). [3]EQ1-4. *Do you know what eclipses are? What causes eclipses?* Probed knowledge and recall. [4]EQ2. *Tell me about eclipses?* afforded generative responses. [5]EQ3. *Have you seen an eclipse?* invited recitation and imagination. [6]Barsalou (2003).

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Figure 5. Drawing of the Earth and Sun to explain the Seasons

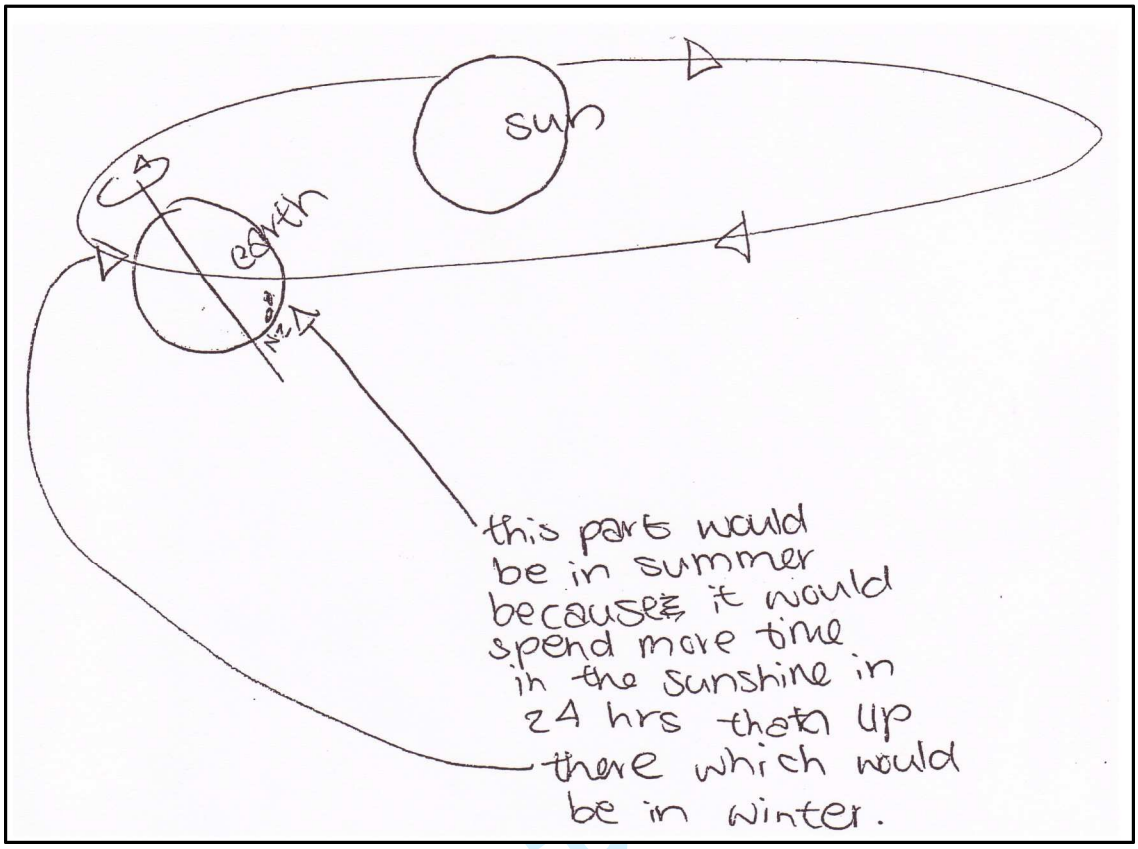

Figure 5a. Drawing of the Seasons by Alice (14, 3) during New Zealand Survey (2003).

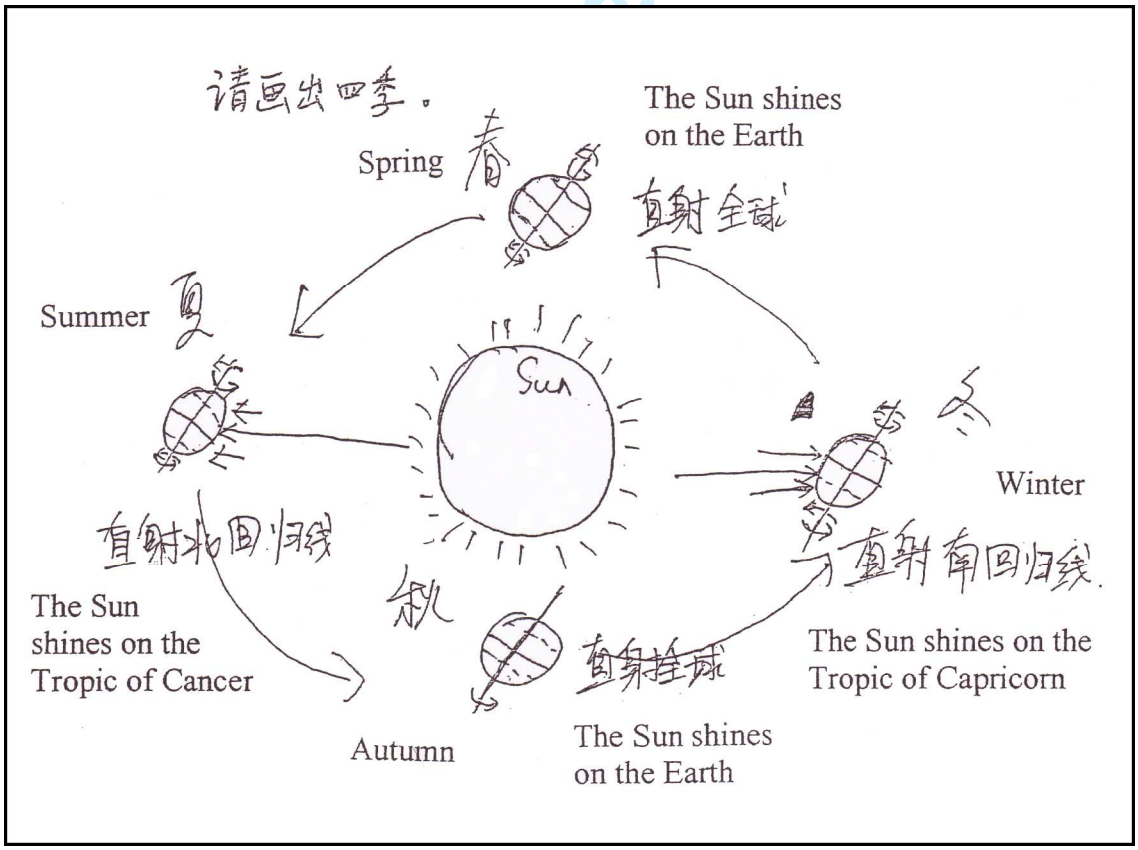

Figure 5b. Drawing of the Seasons by Li Hong Gang (16, 3) during China Survey (2004).

Figure 6. Drawing Earth, Sun and Moon to explain Eclipses

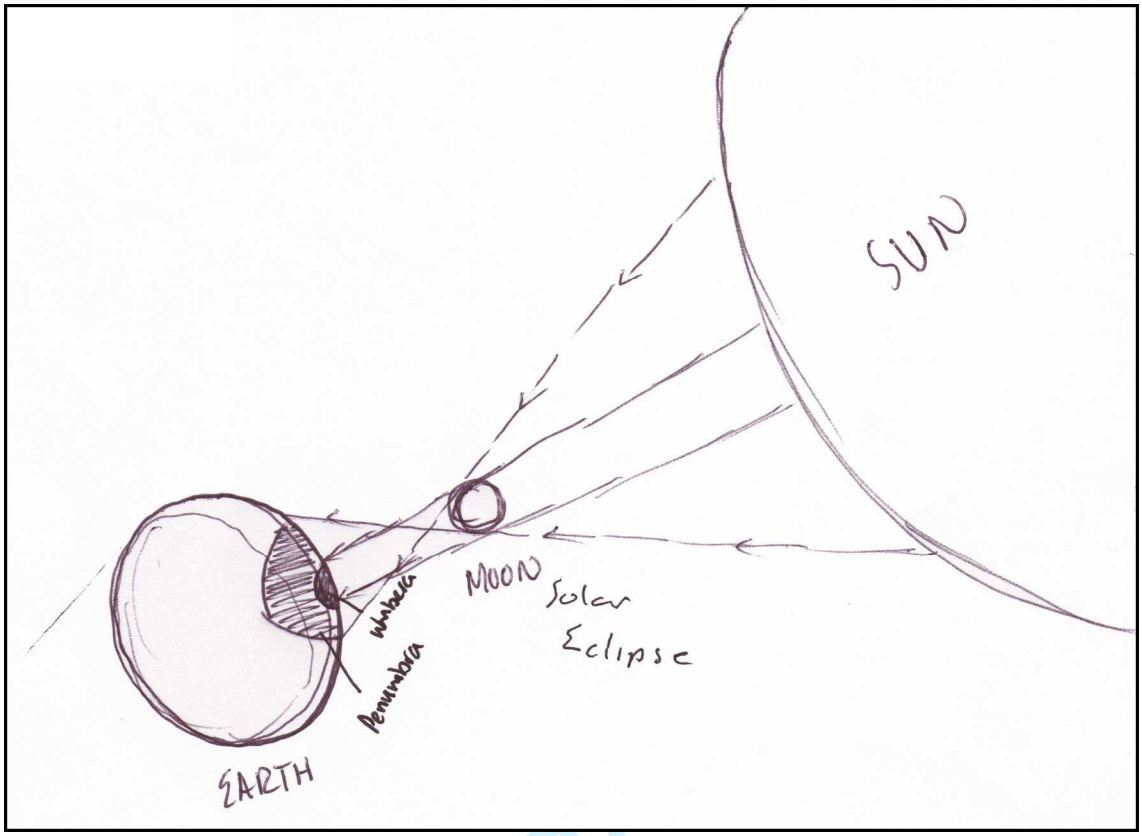

Figure 6a. Drawing of Solar Eclipse by Robin (16, 8) during New Zealand Survey (2003).

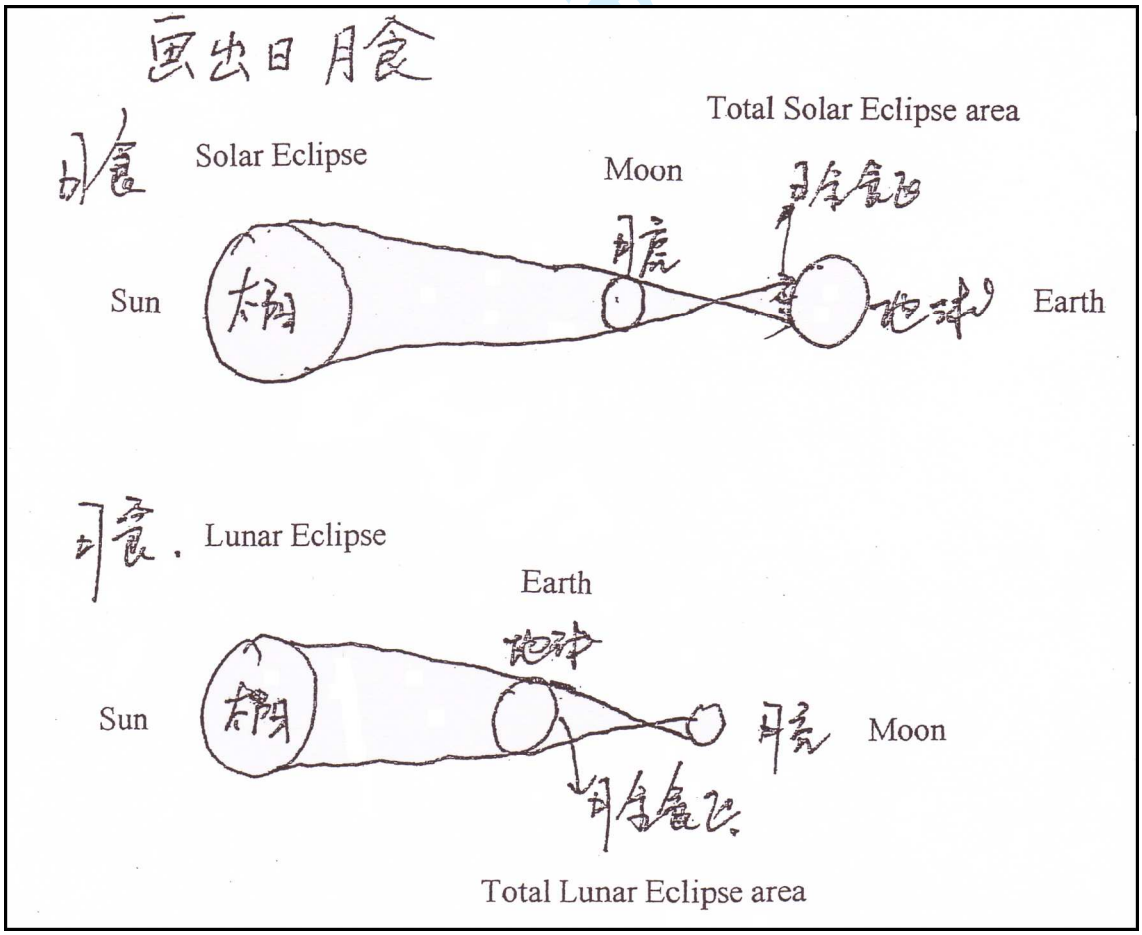

Figure 6b. Drawing of Solar and Lunar Eclipses by Xiao Yang (18, 0): China Survey (2004).

Figure 7. Earth Shape: Concept Category Means

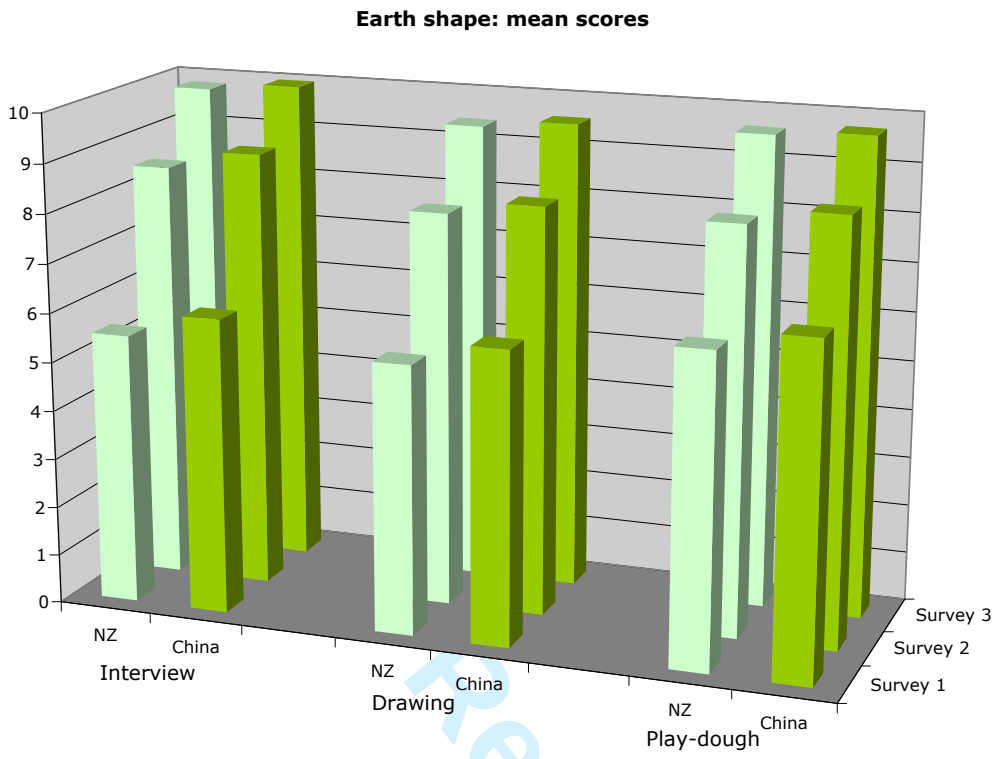

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Figure 8. Earth Motion: Concept Category Means

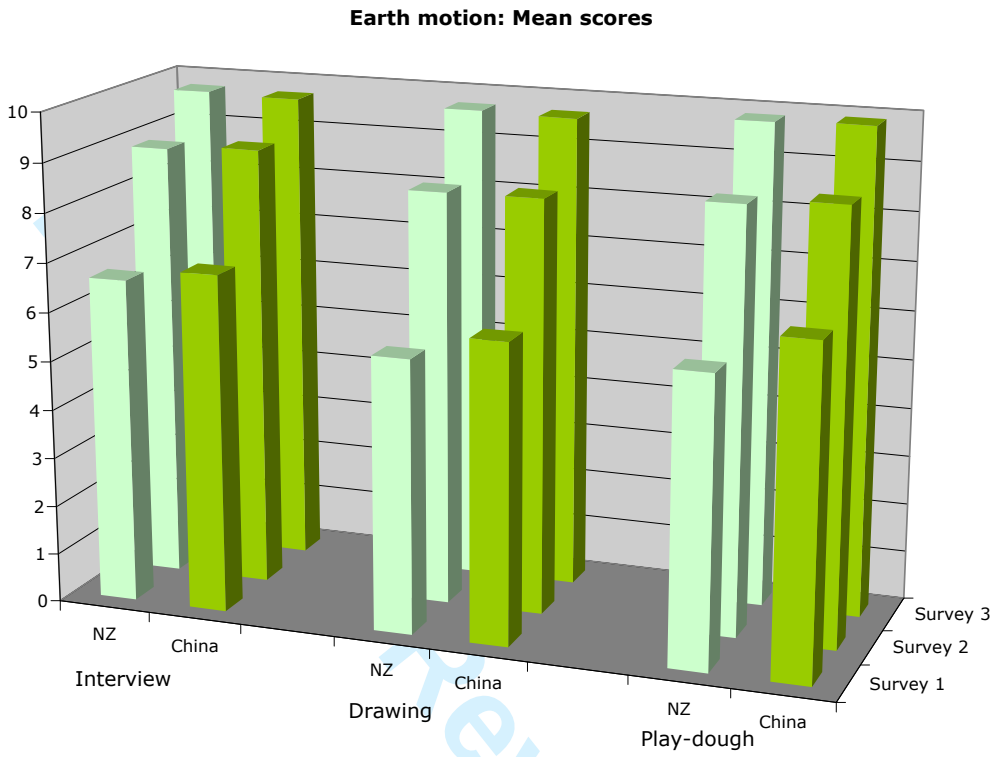

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Figure 9. Seasons: Concept Category Means (3rd Survey)

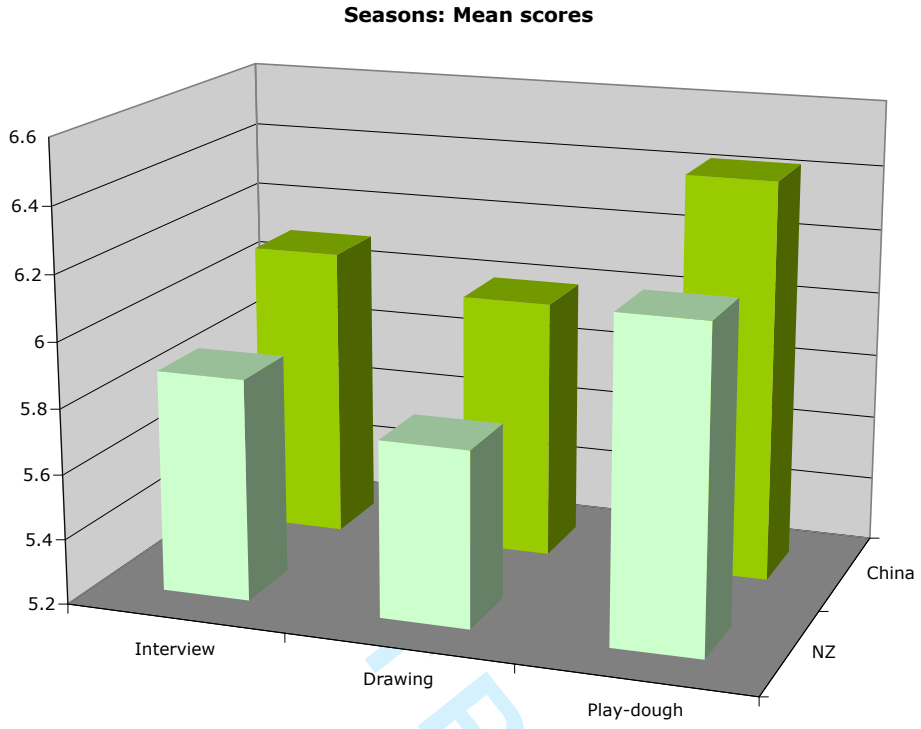

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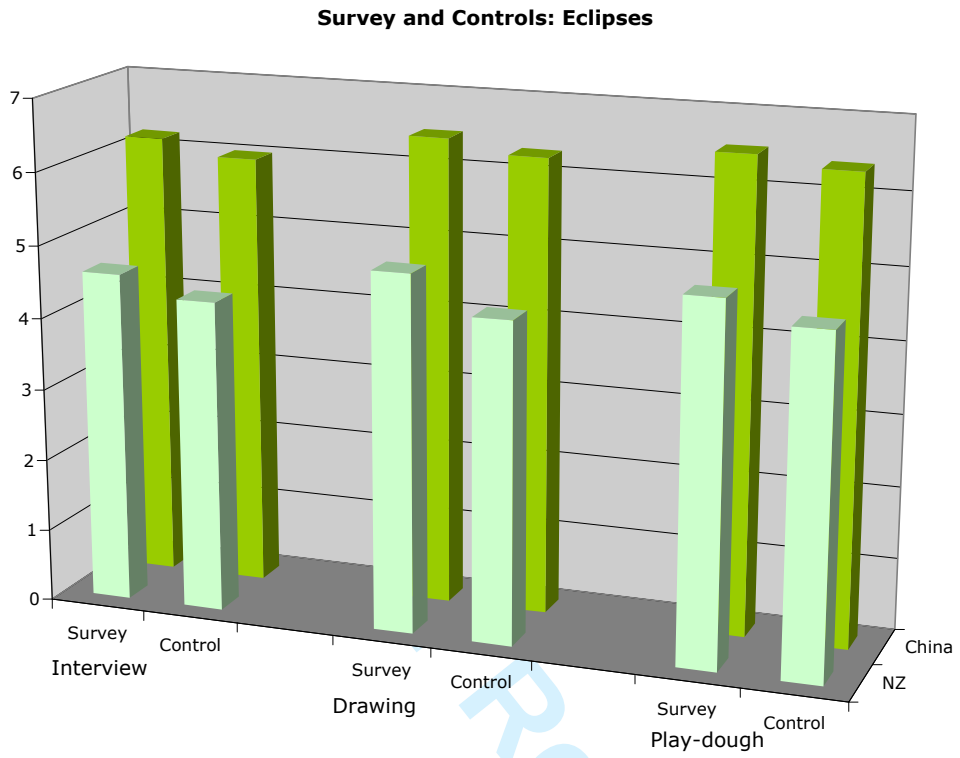
Figure 10. Eclipses: Concept Category Means (3rd Survey)



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