International Journal of Science Education
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tsed20

Evolutionary Maps: A new model for the analysis of conceptual development, with application to the diurnal cycle

Manuel Navarro[a]

[a] Departamento de Didáctica General y Didácticas Específicas, Universidad de Alicante, Didáctica General y Específicas, San Vicente del Raspeig, Spain

Published online: 08 Nov 2013.

International Journal of Science Education, 2013
http://dx.doi.org/10.1080/09500693.2013.855343

Evolutionary Maps: A new model for the analysis of conceptual development, with application to the diurnal cycle

Manuel Navarro*
Departamento de Didáctica General y Didácticas Específicas, Universidad de Alicante, Didáctica General y Específicas, San Vicente del Raspeig, Spain

This paper presents a model of how children generate concrete concepts from perception through processes of differentiation and integration. The model informs the design of a novel methodology (*evolutionary maps* or *emaps*), whose implementation on certain domains unfolds the web of itineraries that children may follow in the construction of concrete conceptual knowledge and pinpoints, for each conception, the architecture of the conceptual change that leads to the scientific concept. Remarkably, the generative character of its syntax yields conceptions that, if unknown, amount to predictions that can be tested experimentally. Its application to the diurnal cycle (including the sun's trajectory in the sky) indicates that the model is correct and the methodology works (in some domains). Specifically, said emap predicts a number of exotic trajectories of the sun in the sky that, in the experimental work, were drawn spontaneously both on paper and a dome. Additionally, the application of the emaps theoretical framework in clinical interviews has provided new insight into other cognitive processes. The field of validity of the methodology and its possible applications to science education are discussed.

Keywords: *Conceptual change; Conceptual development; Primary school*

Introduction

This research intends to improve our understanding of how concepts develop and to use this knowledge to facilitate the introduction of new instructional tools to the science education community. It stems from a previous project (Navarro, 2011) consisting of the design of teaching sequences on the earth and sun system for primary

*Departamento de Didáctica General y Didácticas Específicas, Universidad de Alicante, Didáctica General y Específicas, San Vicente del Raspeig, Spain. Email: manuel.navarro@ua.es

school students. The design of the learning goals and assessment methods prompted the author to reflect on the itineraries that learners might follow and, more generally, on the mechanisms of conceptual change.

Research on conceptual development and conceptual change since the early 1980s has focused largely on the identification of children's ideas, particularly within the so-called alternative conceptions movement, which produced lengthy inventories of children's erroneous conceptions. During the last decade, research on learning progressions has integrated children's ideas into plausible itineraries, from naïve conceptions to scientific ones. This differs from previous, and some on-going, research programmes that focus on the mechanisms of conceptual change (see 'Theoretical Framework' section). This research builds on all of these traditions by seeking to identify the processes underlying the generation of children's (concrete) conceptions,[1] in order to derive from these the web of paths that children may follow—i.e. the set of all conceptions available to children and the (developmental) order relations between them. This development joins other deliberate efforts to apply cognitive developmental psychology to science education.

Theoretical Framework

This section describes the theoretical makeup that has informed the development of evolutionary maps (emaps). The literature on conceptual change is immense, and I will only refer to that which is directly relevant to this proposal. Clearly, the debate on how knowledge develops is far from being resolved or without controversy, and the validity of emaps depends fundamentally on its empirical success.

Concepts are Constructed from Perception

The emap methodology rests on the understanding that, similar to how percepts result from the re[-]cognition of sensations (Mahner & Bunge, 1997, pp. 68–69), conceptual knowledge develops from the re-cognition of percepts, as noted by eminent thinkers such as Bunge (Mahner & Bunge, 1997), Damasio (2006), Edelman (Edelman & Tononi, 2000), Lakoff (1987), Llinás (2002), Merleau-Ponty (2002), Piaget (1986), Piaget and Garcia (1989) and Varela (1991).[2] Many authors have tried to explain this 'ascension', notably Piaget (empirical and reflective abstraction leading to adaptation of schemes), Fischer (skills micro-adaptation according to transformational rules, 1980), Karmiloff-Smith (hierarchical representational re-description, 1992), Mandler (perceptual analysis, 1992) and Mounod (hierarchical reflection of 'practical' and 'conceptual' forms, 1993). These authors' theories differ in many aspects and developmental time frames but agree that, starting with perception, some properties differentiate and integrate into new patterns of increasing abstraction that are selected—roughly speaking—to provide a better fit with the environment (physical and social), eventually reaching consciousness (explicitation). In other words, the conceptual system does not originate as a translation of perception, but as a new construction that matures as it adapts to empirical reality (to decrease uncertainty about the outside world, according to the Bayesian theories of the brain, e.g. Knill & Pouget, 2004). Grounding cognition in embodied (sensorimotor) experience continues to be a dynamic research programme (see Pecher & Zwaan, 2010).

Perceptual representations contain more information than can be manipulated by the brain. Indeed, in the rare cases of eidetic (photographic) memory, the subject seems unable even to access this memory randomly and must move backward and forward as in a videotape (private correspondence with the tutor of savant S. Wiltshire: Szipola, March 31, April 1, 2, 14, and 15, 2008). Consequently, in the process of conceptualization, the brain extracts limited aspects of perceptual experience to form (elementary concrete) concepts. These (simplified) images can be stored in long-term memory and allow children to re-present to themselves and manipulate objects and events in working memory, particularly in the visual sketchpad (Baddeley, 1999). According to Mandler (1992, p. 588):

> Imagery allows infants to re-present objects and events to themselves, and so it provides the foundation for the beginning of thought.

Conceptual Evolution Occurs Through Processes of Differentiation and Integration

The abstraction of concrete concepts from perception involves *differentiating* figures from their background, as emphasized by Gestalt psychology. This differentiation occurs at the perceptual level from sensations—as all animals with full-blown vision necessarily do—and at the conceptual level from perceptions—for which many examples are provided later in this paper. These abstractions are primary differentiations but may be further differentiated into more fundamental units (i.e. previous urelements may be replaced by finer ones). For example, a girl may conceptualize the colour blue and later realize that there are different hues of blue. Or, she may differentiate dogs from other four-legged animals and later begin differentiating distinct breeds (see Mandler, Bauer, & McDonough, 1991). Notice that it is very easy to distinguish two dogs of different breeds through perception; it is the conceptualization (e.g. the capability to recall two distinct images) which requires additional constructive processes. As more differentiations are abstracted from perception, the number of potential integrations increases (the number of dimensions of concept space augments). Differentiations are frequently thought of as yielding binary outcomes, but they may be higher order or even continuous, as is the case with the conceptualization of a magnitude that can vary continuously—however, parameterizations are also integrations by establishing a bijective relationship with real numbers. Differentiation creates new degrees of freedom and can be defined as an increase in the discriminating ability of the (cognitive) system. Clearly, the process of primary differentiation happens from all of the senses—albeit principally from vision—and at all ages (Goldstone & Barsalou, 1998), such as when adults learn to taste wine, differentiate the timbre of certain musical instruments, or recognize a new breed of dog after having seen a sufficient number of them.

The evolution towards increasingly complex concepts results from a repeated process of integrations, some of which entail new differentiations (Siegler & Chen, 2008). When variables are integrated by a Cartesian product (i.e. when they are combined), the number of degrees of freedom of the cognitive system increases. When variables are coupled, by rules, some of those potentialities are pruned. For example, one may combine the variable *number-of-heads* with the concept *dog* and conceive a thrice-headed dog (Cerberus), which is, however, ruled out by the one animal-one head rule. Integrations that are not judged to be possible can still be thought as fantasy.

Patterns common to many perceptual experiences can be abstracted into *image schemas* (Lakoff, 1987)—e.g. the *source–path–goal* or *trajectory* schema—which constitute order by creating relations between individual images, and may be used later for recognition or imagination, even of abstract concepts (Gibbs, 2010). According to Mandler (1992, p. 587):

> Infants use this mechanism [perceptual analysis] to redescribe perceptual information into image-schematic format. [..] redescription into image-schematic format simplifies perceptual information and makes it potentially accessible for purposes of concept formation and thought. In addition to enabling preverbal thought, image-schemas provide a foundation for language acquisition by creating an interface between the continuous processes of perception and the discrete nature of language.

Summarily, 'conceptual understanding should progress from undifferentiated earlier forms to progressively more differentiated and complexly integrated ones' (Siegler & Chen, 2008, p. 436). However, while abundant research supports the idea that all cognition is grounded in sensorimotor experience, conceptual structures take many forms and can be analysed in different ways (e.g. diSessa, 2002; Linn, 2006; Medin, Lynch & Solomon, 2000; Raftopoulos & Costantinou, 2004). Even some concrete concepts, such as *proton*, present complex architectures that cannot be explained as mere combinations of images. Thus, prior research in conceptual change may have vastly underestimated its complexity and diversity, and a systems or ecological view of concepts involving many types of entities and relations may be required (diSessa, 2002). In particular, little progress has been made to explore the architecture of abstract concepts (Crutch & Warrington, 2005; Medin et al., 2000) and little is known about how abstract concepts are represented and used to interpret experience (Wilson-Mendenhall, Simmons, Martin, & Barsalou, 2013). However, a recent meta-analysis of 19 neuroimaging studies concludes that there is a 'greater engagement of the verbal system for processing of abstract concepts and a greater engagement of the perceptual system for processing of concrete concepts, likely via mental imagery' (Wang, Conder, Blitzer, & Shinkareva, 2010, p. 1466).

The concepts of differentiation and integration have been used abundantly in classical development theories and have recently attracted new interest as tools for conceptual analysis, specifically in the context of developing learning progressions and/or teaching sequences (e.g. Buty, Tiberghien, & Le Maréchal, 2004; National Research Council, 2007; Scott & Driver, 1998; Smith, Wiser, Anderson, & Krajcik,

2006) and in the broader context of cognitive development (e.g. Bernstein & Waber, 2007; Case & Mueller, 2001; Demetriou & Raftopoulos, 2004; Fischer & Immordino-Yang, 2002; Schwartz & Fischer, 2004; Siegler & Chen, 2008).

Other Considerations

This framework meets the 'external grounding' (concepts' meanings depend on their connection to the external world) as well as the 'conceptual web' (concepts' meanings depend on their connections to each other) accounts of the meaning of (individuals') concepts. These properties are both necessary and complementary according to some thinkers (e.g. Goldstone, Feng, & Rogosky, 2010). The anchoring of concepts in perception solves the grounding problem, whereas the unfolding of structures, through differentiation and integration, explains their relational and evolutionary dimension.

Finally, the emap framework recognizes variability in individual subjects, in addition to differences in developmental trajectories, as explained in the dynamic conception of cognitive change based on dynamic systems theory (e.g. Raftopoulos & Costantinou, 2004; Thelen & Smith, 1996; Yan & Fischer, 2002).

Research on the Diurnal Cycle and the Representation of Space

Although many studies on childrens' and adults' conceptions of the earth–sun system exist (see, *inter alia*, Atwood & Atwood, 1996; Baxter, 1989, 1998; Bryce & Blown, 2006; Kikas, 1998; Roald & Mikalsen, 2001; Sadler, 1998; Sharp & Kuerbis, 2006; Siegal, Butterworth, & Newcombe, 2004; Trumper, 2001; Vosniadou, 1991; Vosniadou & Brewer, 1992, 1994; Vosniadou, Skopeliti, & Ikospentaki, 2004, 2005), they refer overwhelmingly to the view from space (i.e. the shape of the earth and/or the relative movement of the two bodies) rather than the view from earth (i.e. the observational conceptions; see Note 1), which is the subject of this research. Indeed, the only observational conceptions regarding the diurnal cycle that I have found in the literature (with the exception of several articles by Plummer; see next paragraph) are: *day is replaced by night; the sun shines in the daytime, the moon replaces the sun at night; clouds cover the moon at night; the sun and moon move up and down; the sun goes behind mountains at night*. Accordingly, these studies focus on synthetic conceptions rather than preconceptions, which are the conceptions investigated predominantly herein (see 'Emaps' section). In addition, they do not provide itineraries (again, excluding Plummer's articles) or underlying structures. Thus, this section is brief.

As said, the only noteworthy exception to the above known to this author is a recent study (Plummer, 2009; Plummer & Krajcik, 2010) that quantitatively examines children's understanding of the patterns of celestial motion, including the moon and the stars, at different grade levels, proposes a learning progression for celestial motion and assesses the effect of an instructional intervention. Whereas the scope of the above empirical study is much wider than that of this article, it is, in comparison, coarse-grained and does not seek to identify the underlying mechanisms of change. The only constructs about the sun's diurnal cycle that it includes in the progression are: *the sun rises/sets during the day; the sun is in the sky during the day and not at night; the sun's motion is continuous; the sun rises/sets on opposite sides of the sky; the sun does not pass through the zenith*.

This research has also revealed the process of differentiation and integration of space that children must follow before they construct a trajectory for the sun (see 'Other Findings' section). It was later found that this is consistent with previous research by Case, Stephenson, Bleiker, and Okamoto (1996), which describes how children develop a conceptual representation of space by progressively integrating additional dimensions (or, in their parlance, axes) and altering these structures from discrete to continuous.

Emaps

What Emaps are and How They are Made

The theoretical framework argued that some concrete concepts develop through the differentiation of schematic images from perception (visual or otherwise) and the subsequent integration of these images. Emaps tries to mirror this process to map the different pathways that children may follow in the construction of concrete knowledge in specific domains. Consequently, emaps does not seek to identify children's conceptual evolution by observing the phenomenic layer (the usual way, which requires longitudinal studies), but by proposing some underlying mechanisms, constructing from these what the phenomena should look like, and testing these predictions empirically (i.e. by using the far more powerful hypothetical-deductive method).

In other words, emaps delve into an underlying and parsimonious layer comprising perceptual differentiations from which some concrete conceptions are derived by combining (integrating) the different values afforded by the differentiations (which may be discrete or continuous). Said relations can take many forms, such as class, order, attribute, spatio-temporal relations (topological, projective, Euclidean) and causal relations. The (generative) syntax of emaps defines the constructs that belong to the map. Its semantics relate those constructs with the child's mental model through 'expressed models' (see Gilbert, Boulter, & Elmer, 2000), such as drawings. Emaps are *partially ordered sets*, in which the hierarchical (or complexity) level is defined by the number of differentiations.[3] Development occurs in the direction of increased complexity. Obviously, the higher the complexity, the greater the demand on mental resources.

Emaps are developed tentatively through epistemological reflection, beginning with the parsing of some prototypical concepts in the target domain, in order to identify the elementary differentiations (urelements) and the types of relations (if target concepts cannot be parsed in this way, the domain is not amenable to emaps methodology), and, in principle, proceeding with all the possible integrations of these urelements. However, registering all the possible integrations soon becomes unmanageable and the designer will apply expert judgement to exclude (from the representation of the map) those that appear particularly implausible. Tentative completion of the map requires that it explains all the scientific concepts and all the incorrect conceptions known from previous research as integrations of primary differentiations.

Empirical Strategy

Both the differentiations and the integrations in an emap are defined very precisely; therefore, the model output is unambiguous. Importantly, this level of precision in the deductive process makes possible the use of the hypothetical-deductive method (predictions can be tested unambiguously). If the emap 'predicts' all the data (children's conceptions) known from previous research (i.e. if it explains existing experimental data), it is validated by retroduction (see Lawson, 2010)—according to the symmetry thesis there is no *logical* difference between explaining and predicting (see Ruben, 1992, p. 124). Most cogently, if some of the derived conceptions are found posteriorly, the emap is validated in the archetypal predictive fashion of the hard sciences. Contrary to some learning progression methodologies, conceptions revealed by empirical research on an emap cannot just be added to the design in an appropriate place. Instead, it must be possible to assemble them from primary differentiations, which will assign a well-defined position in the overall structure. If this assembly proves unfeasible, the emap fails.

While some conceptions may be removed from the emap after the empirical tests (not all that is possible is always realized), it may happen (and indeed it has happened in this project, see 'Results and Discussion' section) that some constructions that were initially judged to be extremely unlikely are later found in children's productions. It should be noted that these productions will be recognized as (the expression of) mental forms, instead of merely as experimental noise, because they are compatible with the syntax of the map. Various lateral connections with related areas (e.g. in this case, clouds) or vertical connections with more abstract knowledge (e.g. the sun moves in the sky because the earth spins) are absent by design, but they may appear in the empirical research.

Discussion

Emaps reveal, in great detail, the mechanism of conceptual change. Specifically, they indicate which differentiations are missing and which integrations must be made or modified to evolve from an incorrect conception to a scientific concept (some examples are given herein). In addition, emaps help differentiate knowledge that is erroneous due to incorrect integrations (knowledge that is wrong and requires some undoing) and knowledge that is not scientific due to missing differentiations (knowledge that may not be false despite not being scientific). The latter may suitably be called *rudimental conceptions* to differentiate it from other kinds of non-scientific conceptions—see example in next section. Given the nature of target knowledge, incorrect conceptions emerging from this research are likely to consist, predominantly, of naïve ideas or preconceptions, rather than synthetic models. Rudimental conceptions are a well-defined class of preconceptions. It can be noted that this framework integrates the misconception-based ‘fix it’ view of conceptual change and the intuition-based ‘work with it’ view of conceptual change (see Duschl, Maeng, & Sezen, 2011).

Emaps can be seen as a micro-developmental methodology, but it is focused on the construction of concepts rather than skills. Micro-development is understood as development that takes place during a short time span; in turn, [macro]development evolves through reiterated micro-developmental sequences in which variability plays a key role in self-organization (Granott, 2009). Thus, micro-development (and Emaps) theory is consistent with evolutionary epistemology (e.g. Campbell, 1974, 1987; Czico, 2000; Dennett, 1995/1996; Edelman & Tononi, 2000; Popper, 1972/1979; Powers, 1973; Siegler, 1999)—in fact, this is the origin of the maps’ epithet. In micro-developmental theory, each level represents the increasingly complex coordination [integration] and differentiation of earlier levels (Schwartz & Fischer, 2004). Each person functions at diverse levels depending, amongst other factors, on the demands of the task domain and scaffolding (Yan & Fischer, 2002). It will become clearer in the next section that emaps coincide with other micro-developmental analyses and modelling techniques in that ‘children follow diverse skill-building pathways to arrive at the “same” point. Understanding the shapes and processes of these pathways, as well as teachers’ roles in them, will make it possible to individually tailor teaching and assessments’ (Fischer & Immordino-Yang, 2002, p. 43).

Tentative Design of the Diurnal Cycle Emap

The tentative design of the diurnal cycle emap is shown in Figure 1. Arrows indicate which differentiations participate in each integration (conception). Inversely, the map shows what integrations are possible for a given set of differentiations and, consequently, which additional conceptions are possible when another differentiation is made.

Day/Night Cycle

Presumably, the first differentiation that occurs regarding the day/night cycle is between lit and dark skies. The subsequent integration is that of a cyclic succession, and both phenomena are symbolized by the day and night lexemes. The concept of the sky may not be available and may instead be replaced by that of ‘clouds’ (light blue, dark blue, black). Another early differentiation would be that of the sun, and subsequent integrations may include the following: *sun-in the sky* and *sun-lit sky*, *no sun-dark sky*. The need to recognize the presence of the sun in the sky when it is obstructed by clouds makes this process more demanding. This integration can take on a causal meaning if the relationship between the sun and daylight is interpreted causally and not as mere coincidence, i.e. descriptively (which is not trivial, as we will see). Similarly, the moon will also be differentiated, and it may be integrated as *night-moon, day-no moon* (a common misconception, more on this later). This is summarized in the left -hand side of Figure 2, under ‘day/night cycle’.

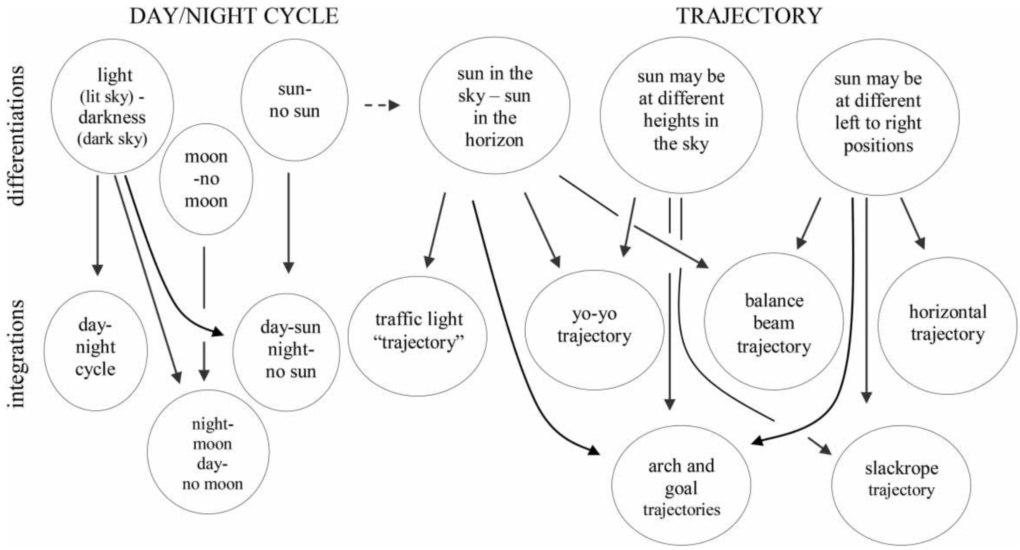


Figure 1. Schematic emap of the diurnal cycle, including the sun's trajectory in the sky
Notes: 1. Includes the most frequent integrations. Others are possible. Arrows indicate which primary differentiations participate in each integration.
2. A differentiation of the trajectory in a certain direction implies that space has already been dimensionalized in that direction (see Other Findings).

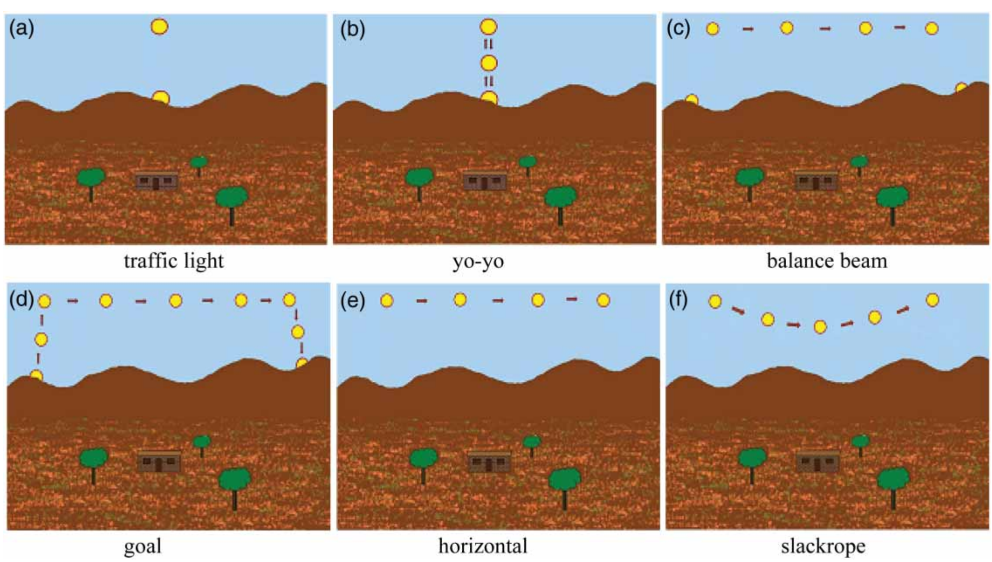


Figure 2. (a–f) Main trajectories of the emap other than the correct arch-shaped trajectory (the direction of the movement may be inverted)

Trajectory

A subsequent developmental step is expected to consist in the differentiation of the presence of the sun in the horizon (vs. fully in the sky); later, it would be integrated with the beginning and with the end of the day, leading to a four-step cycle (night, dawn [sun in the horizon], day [sun above], dusk [sun in the horizon]). I call this cycle the *traffic light trajectory* (Figure 2(a)). In this conception, the sun does not follow a true trajectory; rather, it is simply in one of two or three positions (depending on whether the sunrise and sunset positions have been differentiated).

In a separate development, the sun begins moving in the sky. The construction of a trajectory, which is facilitated by the prior existence of the *trajectory schema* (see 'Theoretical Framework' section), involves two continuous differentiations, such that the sun may occupy different horizontal positions and different vertical positions, combined with the corresponding integration. Thus, it involves the transformation of a discrete degree of freedom into two continuous degrees of freedom. Consequently, we have many possible integrations. If only the vertical differentiation is achieved, it seems likely that the sun will appear on the horizon, rise to its zenith, stay there or not, and go back down again (*yo-yo trajectory*; Figure 2(b)). If only the horizontal differentiation is constructed, the sun will appear on the horizon, jump above, and probably follow a horizontal path until it falls back to the horizon (*balance beam trajectory*; Figure 2(c)). To construct the correct arch trajectory, both differentiations must be present, even though other integrations are possible (e.g. gradually up, horizontal displacement, gradually down, *goal trajectory*, Figure 2(d)). If the horizontal differentiation occurs before awareness of the position of the sun in the horizon and of vertical displacement, then the trajectory is likely to be a horizontal line (Figure 2(e)). If there are vertical and horizontal differentiations but no differentiation of the sun in the horizon, the most likely trajectory is the *slackrope* (Figure 2(f); while this trajectory was not considered before the experiment, it is fully consistent with the model; this issue will be discussed later in the paper). This is summarized in the right -hand side of Figure 1 under trajectory. To note that until the well -documented conception that the sun follows one's movements is superseded, the integration of the sun's trajectory cannot begin (more on this issue later).

Discussion

The emap of the diurnal cycle shows clearly how the same scientific knowledge can be reached through different pathways. For instance, if the child differentiates the position of the sun in the horizon first, then its vertical movement, and finally its horizontal movement, he or she will probably initially conceive the traffic light trajectory, followed by the yo-yo trajectory, and finally the arch (or goal) trajectory. If the inverse sequence of differentiations applies, the horizontal trajectory will likely be followed by the fixed beam before moving to the arch (or goal). Likewise, erroneous conceptions can be reached by different alternative pathways. Importantly, the structure of the emap describes precisely the nature of the changes that the child must accomplish to attain scientific knowledge. For instance, if the child draws the yo-yo trajectory, he or she must learn that the sun also moves from left to right (horizontal differentiation) and must integrate this movement with the vertical movement.

This emap also illustrates the aforementioned rudimental conceptions. According to the emaps framework, concepts that are scientifically correct consist of a number of primary differentiations coordinated in specific ways. If the differentiations are there but the integrations are incorrect, we have an erroneous conception that requires some undoing to get to the correct place. A typical example is the goal trajectory. A less known and more interesting case occurs when one or more differentiations are missing. If the integrations made with the available differentiations are correct, the corresponding knowledge will not be scientific, but it may not be false either. For instance, in the traffic light trajectory (no spatial differentiations), the child knows that the day begins and ends with the sun in the horizon and spends the rest of the day in the sky. This knowledge is not complete, but it is not untrue either. It can be noted that, in this case, no undoing needs to occur and that before attempting to teach the shape of the trajectory, the necessary differentiations must be achieved, a task which is more complex than it may initially seem (see 'Other Findings' section, dimensionalization of the sky). Of course, it is possible to find conceptions that present both features, for instance, the slackrope trajectory.

Importantly, the differentiations and integrations involved in the construction of the sun's diurnal cycle are fundamental for the development of the annual cycles, that is, the regularities in the value of the culmination of the sun and in the values of the azimuth and time of sunrise and sunset. Furthermore, the heliocentric system can only be linked with empirical reality as an explanation of the above-mentioned regularities, a 'big idea' in the discipline (Plummer & Krajcik, 2010). Indeed, instruction that covers actual celestial motion without also covering apparent celestial motion will not lead to an accurate understanding of the latter (Plummer, 2009). The emap for the yearly cycle has been summarized elsewhere (Navarro, 2011).

Research Goals and Empirical Methodology

This research contains two distinct parts, with different goals and methodologies. They are united by the theoretical framework, the experimental set up and, particularly, the fact that the research questions of Part 2 derive from the application of Part 1 (i.e. Part 2 is an outgrowth of Part 1).

Part 1

This is the main part of the empirical research. Its fundamental goal is to assess whether emaps is a methodology that maps accurately the web of paths that children may follow in the development of certain concrete concepts (those that can be parsed as integrations of images, visual or otherwise). This question is made operational by restricting it to the day and night cycle, including the daily trajectory of the sun in the sky. Accordingly, the direct goal is to assess the correctness of this emap, and the indirect goal to determine whether emaps methodology, and theoretical model, work in some (concrete) domains.

The methodology for emap validation has been discussed in general terms in the previous section describing emaps. This emap will be endorsed by the experimental data if some of its predictions are confirmed and any other finding can be unequivocally explained as integrations of the primary differentiations. Since this methodology is rather unusual in the social sciences, which may lead to misunderstandings, I will propose an analogy for clarification. Let us suppose that some researcher makes a development of the theory of evolution that enables him or her to predict the existence of certain species. Let us also suppose that he or she predicts the existence of a blue insect with two pairs of wings on its head and of another insect, coloured green, with eight pairs of purple eyes in the back, both in specific habitats of the wet forests. Finally, let us suppose that an ad hoc team visits the jungle and, wonder of wonders, the two insects are found precisely as predicted by the researcher. In addition, two other unknown insects are discovered, and they fit perfectly well with the theory. No doubt, the latter would have been strongly supported, regardless of statistical analysis or sampling procedures. Similarly, this emap propounds a number of, rather exotic, trajectories that correspond to the different degrees of differentiation and to the potential integrations, many of which were not known to be held by children (at least not to this author), and, therefore, makes predictions. If some (or, even better, all) of these unheard of trajectories are drawn spontaneously and unequivocally by the participating children and if any unpredicted trajectory fits well with the model, emaps will be cogently supported in the characteristic fashion of the hard sciences. Thus, this research meets the challenge posed by diSessa (2002) when he affirms '[t]heoretical vagueness and imprecision trickle down and reinforce a tendency to use data impressionistically or merely statistically, without putting strong hypotheses about what is involved in conceptual change to strong tests'. As the Nobel laureate Roald Hoffman has said, there is nothing as powerful as a prediction that is not obvious and is proven right.

In addition to making verifiable predictions, the hallmark of science (sensu stricto), this emap benefits from a characteristic that makes its empirical validation particularly robust, namely the visual nature of its contents (compared, for instance, with the properties of materials), as drawings allow researchers to elicit students' ideas without imposing pre-existing expectations (Harlow, Swanson, Nylund-Gibson, & Truxler, 2011). Furthermore, drawings can be reproduced directly, thereby enabling readers to see the key raw experimental data with no intermediation.

More specifically, this first part of the empirical research consisted of two phases. The first phase was conducted over four weeks and involved interviews with students between 4 and 11 years of age who attended the middle-class Ramon Llull school in the Spanish city of Alicante. The lower bound of the range is age four due to the inadequacy of the technique with younger children. The sample was approximately equally split by gender, and over 94% of the children were white. In all, 36 interviews were videotaped. These children (six per grade in pre-primary school and four per grade in primary school) were sorted by their respective teachers, who were instructed to provide a representative sample in terms of academic achievement. These interviews were held in an empty room in the same school and lasted about 10–15 minutes. I explained to the students that the purpose of these interviews was to find out what children of their age think about the day and night and, therefore, that the important thing was that I understood what they think and not whether their answers were more or less correct (wording adapted to age). Questions were pre-defined and followed a fixed algorithm. Interviews consisted of three steps. The first was a brief questionnaire to analyse the constructs of day and night (see the appendix and Figure 3). Second, the child was asked to draw the sun at five different times of the day. These times included just before night-time, the very beginning of the day, lunchtime (approximately 1:30 p.m. and ca. culmination), the morning school break (11 a.m.), and afternoon snack time (approximately 5 p.m.). I did not follow the natural sequence to avoid inducing an order that may have been non-existent in the child's mind. In a few cases, it was judged not to be necessary to request the full sequence. Next, I asked the child to describe the trajectory to ensure, to as large a degree as possible, a correct interpretation of the drawing. Pilot testing showed that the requested behaviour is more demanding than drawing the trajectory as a line (which may be a recollection from a textbook). As some of the younger children's trajectories could not be classified unambiguously (e.g. whether a slightly inclined trajectory was deliberate or just poor craftsmanship), even with the help of the interview, only those that seemed well beyond doubt were used to support the validity of the model (in contrast to other methodologies, in this research this requirement is more stringent, not less stringent, as it prevents false positives). One-third of these drawings were also coded by another researcher with 92% agreement. I have coded the age of the subjects as y:m (years:months).

In the second phase of the research, which lasted about two weeks, I repeated (and videotaped) the full interview with 34 children of similar demographics, who were 6–11 years of age and were sorted using the same criteria, at the summer school of the university in the same city. Again, the interviews were held in an empty room of the school building. These interviews differed in that, before or after sketching the trajectory on paper, they had to signal the position of the sun (at said times of the day) with a laser beam on a dome above their heads, a strategy similar to that of Plummer (2009)

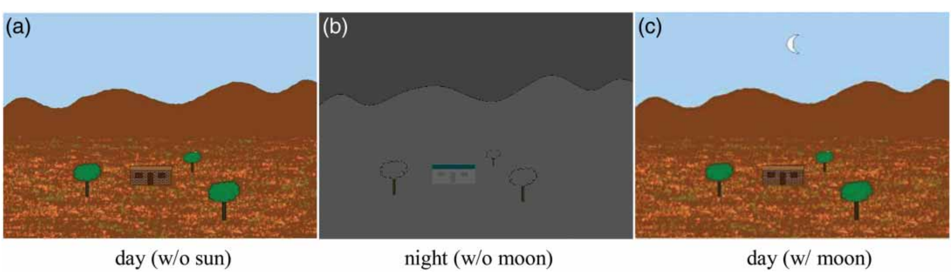


Figure 3. (a–c) Drawings used to detect children's conceptions of the day–night cycle

and Plummer and Krajcik (2010) (see Figure 4). Although it was expected that generally the same trajectories would be drawn on both media, there might occur occasional discrepancies. Whereas the sky is very difficult to dimensionalize (see 'Other Findings' section), it is far easier to dimensionalize the dome. Arguably, this facilitating context might prompt the emergence of conceptions that did not exist explicitly in children's minds, whereas if the child has not conceptualized a trajectory, it is unlikely that he or she will do so while drawing it on paper. On the other hand, some children may not draw on paper the arch trajectory due to the difficulty of representing in two dimensions a trajectory that crosses the celestial dome.

Although the number of children displaying some behaviour is sometimes mentioned, this is not always the case, principally because some of the children's replies are ambiguous or contradictory and cannot be classified unequivocally (see discussion in 'Other Findings' section).

Part 2

After the interviews of part 1 had been completed, I took advantage of both setups to pursue an additional goal of a more open nature. More specifically, said interviews inspired some additional questions, which were explored in clinical interview fashion using, again, the emap framework as theoretical lens. Specifically, I conducted

Figure 4. Experimental setup with dome used in some interviews

over 50 additional interviews (with the same children, and with different children to avoid the conditioning effect of the first interview) to address issues not yet fully understood. All of these interviews were held in the same rooms as above and duration varied widely. They were framed to the students in the same way. The questions that were addressed are listed below.

The clinical method 'pre-dates Piaget and is now accepted practice in this field' (Bryce & Blown, 2006, p. 1123) and serves to 'draw conclusions about the knowledge resources children possess' (Sherin, Krakowski, & Lee, 2012, p. 170). However, it has also received abundant criticism from many researchers, which is principally related to the influence of the setup, rules and interviewer on the mental processes that are being investigated and, consequently, to the possible lack of reproducibility and extrapolability to 'real-world' contexts. The strategies that I have followed that minimize these risks coincide with the advice of diSessa (2007) and Russ, Lee, and Sherin (2012); namely framing the interviews in a way that makes sense and is not intimidating to the interviewees (as an *inquiry* or, in this case, as an *expert interview*—see Part 1—as opposed to an *oral examination*), conducting the interviews in a way that is not coercive or seductive, and proposing tasks that are sensible to the interviewees. The motive driving these strategies from the beginning was, simply, a fundamental respect to the children.

Furthermore, in this part of the project, the interviews have been used to generate conjectures (about the existence of certain cognitive mechanisms), rather than as proof of claims. Instead, claim support consists of outgrowths of the theoretical framework that are consistent with both well accepted theory (as referred to in the framework) and the presented behaviours, and, epistemologically, are introduced as 'inferences to acceptable and best explanation' (see Hon & Rakover, 2001). Accordingly, claims (in Part 2) are not presented as proven but, rather, as plausible conjectures that may deserve further attention from specialists.

The questions that have been explored in these interviews are:

- Why did many children (in part 1 interviews) insist that the sun does not move in the sky (i.e. as seen from where we are) and yet drew it all over the sky at different times of the day?
- Why, at all ages, some children state that the sun moves and others state that the sun is still?
- Why do some children give opposite answers to the same question on different occasions?

Results and Discussion

Regarding the Validity of the Emap (Part 1)

This is the fundamental part of the research. It investigates what conceptions children have about the day/night cycle and the movement of the sun in the sky, and compares these to the predictions made by the emap.

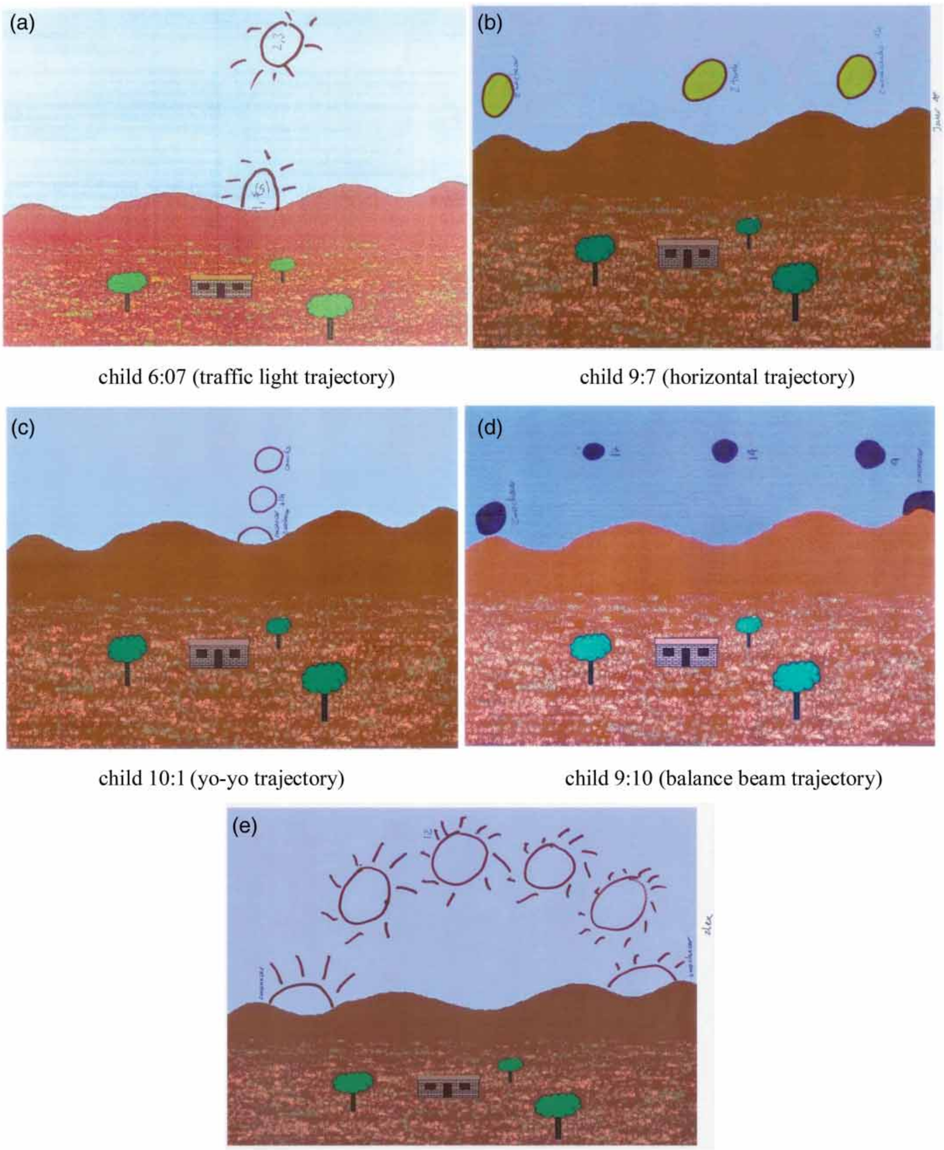
Trajectory. Astoundingly, all of the trajectories predicted by the emap were unequivocally drawn (more than once) by children—see examples in Figure 5. I had particularly distrusted the horizontal trajectory because I had the unjustified belief that the differentiation of the sun's position on the horizon and its integration at dawn and dusk happened very early, before any integration of a trajectory in the sky (but it was included, however, for logical completeness).

These drawings confirm that the sun-in-the-horizon, vertical, and horizontal differentiations are real and do not necessarily occur at the same time or in the same order (for instance, in the traffic light 'trajectory', the sun-in-the horizon differentiation is first, while in the horizontal trajectory the initial differentiation is the horizontal one, and in the slackrope trajectory—see below—the horizontal and vertical differentiations occur before the sun-in-the-horizon). Significantly, most of the children who drew vertical or horizontal trajectories categorically opposed any movement of the sun in the other direction. Expectedly, some of the children drew the arch trajectory (but these were a small minority except in the latter two grades, where 8 out of 20 did).

In addition, there were other well-defined trajectories that were not explicitly predicted but are perfectly coherent with the model or even implied by it. One example of the former is the slackrope (Figure 6(a)). Cases of trajectories implied by the model are: the *half traffic light* (the sun appears high above, stays there, and finally switches to the horizon); the *half yo-yo* (the sun appears high above, stays there, and then descends gradually); the *half balance beam* (the sun appears high above, moves horizontally, and then descends abruptly); and the *half goal* (the sun appears high above, moves horizontally, and then descends gradually), Figure 6(b)–(e) (see in the first section of 'Other Findings' why the apparent horizontal displacement in *b* and *c* should be ignored). These trajectories are similar to some specified by the original emap, except that the integration of the sun in the horizon has been done for dusk but not for dawn. Therefore, they should be added to the emap in the same cells as the corresponding full trajectories, since they are made of the same primary differentiations. These trajectories were not predicted explicitly due to the aforementioned belief that the differentiation of the sun's position on the horizon and its integration at dawn and dusk happened very early and simultaneously, before any integration of a trajectory.

It is reasonable to question why so many of these children's constructs had been previously overlooked. It must be noted in this respect that it is characteristic of complex phenomena that, without a suitable model, data look like noise (Kaneko & Tsuda, 2000, p. 97). Indeed, in the absence of the emap, these children's drawings look like a meaningless hodgepodge.

Unexpectedly, 12 of the trajectories were seemingly random, an event that occurred up until the end of primary school (see Figure 7). In principle, these results can be accounted for by the model as cases of differentiation and lack of integration. In other words, children would know that the sun can be at different positions from left to right and/or different heights but would not have worked out any structure (this topic will be discussed later). Interestingly, two interviews (see Figure 7(a)) suggest a lack of (explicit) integration of the sun with the sky.



child 6:07 (traffic light trajectory)

child 9:7 (horizontal trajectory)

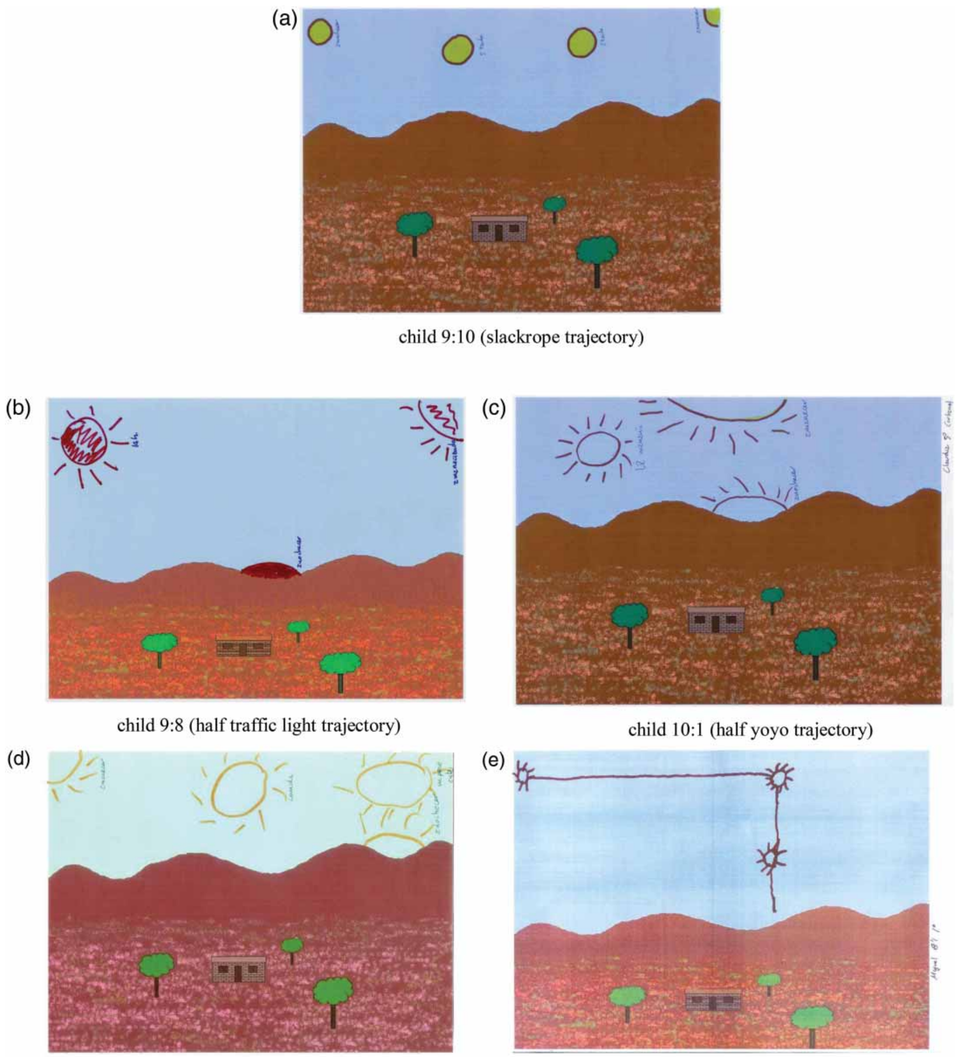
child 10:1 (yo-yo trajectory)

child 9:10 (balance beam trajectory)

child 11:1 (arch trajectory)

Figure 5. (a–e) Examples of drawings of trajectories predicted by the emap (Key: *amanecer* and *1* mean dawn, *recreo* and *2* mean morning break, *comida* and *3* mean lunch, *2 tarde* means 2 p.m. (lunch time), *merienda* means afternoon snack, *anochecer* and *5* mean dusk)

Comparison of the trajectories drawn on paper and on the dome. The research conducted with the dome yields the same findings as that conducted with paper, as the same (predicted) trajectories are found in both settings. Furthermore, 31 children (out of 34) drew the same trajectory (or lack thereof) on both media. In a few cases (three), as



(a) child 9:10 (slackrope trajectory)

(b) child 9:8 (half traffic light trajectory)

(c) child 10:1 (half yoyo trajectory)

(d) child 7:6 (half balance beam trajectory)

(e) child 6:1 (half goal trajectory)

Figure 6. (a–e) Other trajectories drawn by children (Key: *amanecer* means dawn, *mañana* means morning, *comida* means lunch, *tarde* means afternoon, *anochecer* means dusk, *un poco antes* means a bit earlier)

expected, the dome prompts the emergence of a more evolved trajectory. For instance, an 8:5 girl drew the slackrope trajectory on paper but sketched an arch on the dome (i.e. there is a qualitative change that cannot be attributed purely to the difficulty of projecting the arch into a picture). In contrast, in one case (a boy, 10:3) the difference was due to this obstacle: what appeared to be a yo-yo trajectory on paper, in fact, was meant to be an arch, but the child did not know how to draw it on a flat surface. In this case, the concept seems to have existed, but the child did not know how to draw it.

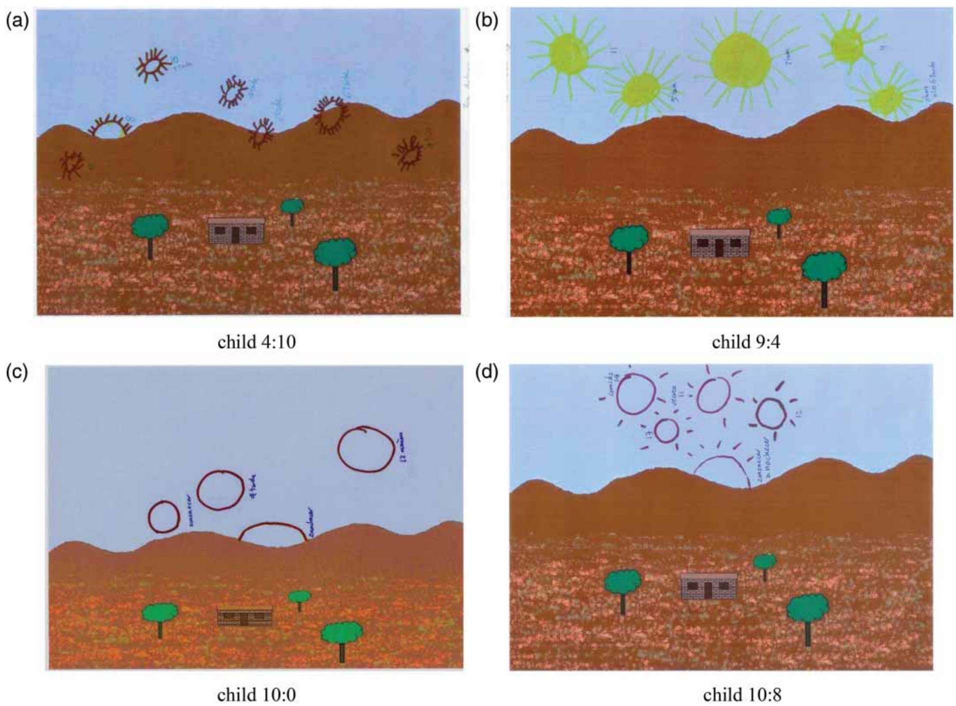
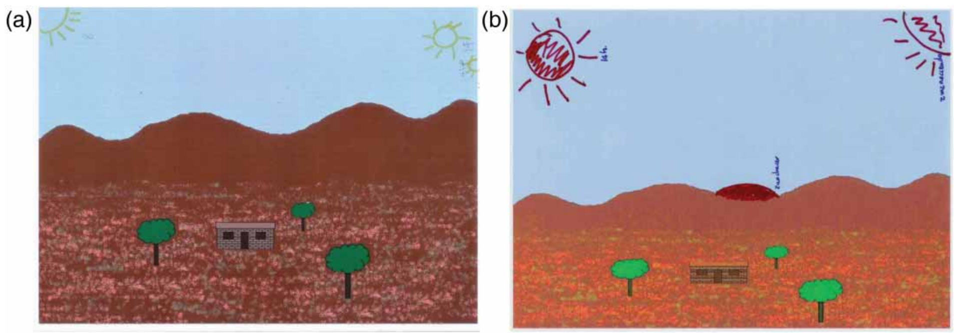


Figure 7. (a–d) Examples of drawings in which the sun's trajectory seems to be random (Key: *amanecer* means dawn, *mañana* means morning, *tarde* means afternoon, *anochecer* means dusk)

Dawn and dusk. Fifteen children (out of 70) did not draw the sun on the horizon at any point of the trajectory, which confirms that this is a key differentiation that cannot be taken for granted. Indeed, it was not until nine years of age that a majority of the children drew the sun on the horizon both at dawn and at dusk, and there were children of all ages who did not (10 out of 19 in the 8–9 years range did, and 14 out of 20 in the 10–11 years range). Younger children did not normally draw the sun in the horizon, and when they did it was mostly at dusk (see Figure 8). Specifically, 4 (out of 12) pre-primary school children drew the sun on the horizon at dusk, and only 1 drew it on the horizon at dawn. The gap between sunset and sunrise awareness was manifested at all ages.

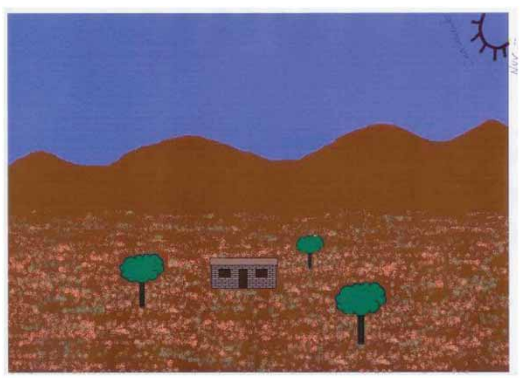
To double-check the unexpectedly high number of children who did not draw the sun on the horizon (as part of the sun's trajectory), I gave them a picture with a dark blue sky and asked them to draw the sun at dusk again. All of them drew it far from the horizon, normally at the edge of the image (see in Figure 9 the corresponding drawing by the author of Figure 8(a)). A girl (8:7) recalled that at dusk, the sky turns orange, but she could not remember the location of the sun. When I insisted, she suggested that the sun was in the middle of the sky.

Although I expected the differentiation of the sun on the horizon and its integration with dawn and dusk to be more prevalent, these results reinforce the model because they show that these elementary processes exist, are highly relevant and cannot be



child 7:7 child 5:10

Figure 8. (a and b) Examples of sun 'trajectories' that do not depict the sun in the horizon or do so only for dusk. 'Child a' has not differentiated the position of the sun in the horizon; 'child b' has differentiated it but has only integrated it at dusk (Key: *anochecer* means dusk, *amanecer* dawn; the age of children has been coded years:months)



child 7:7

Figure 9. Sun's position at dusk. Drawing requested to confirm that the separation between the sun and the horizon at dusk is deliberate (same child as Figure 8(a))

taken for granted. The poor results obtained for this task may be related to the high-rise characteristic of Spanish cities, which makes the observation of sunrise and sunset difficult. In fact, a 5:11 girl who did draw the sun on the horizon said that she had seen it in the village where her parents came from. The gap between dawn and dusk results may be explained as a consequence of children's daily timetables, which make the observation of dusk easier.

Two children drew the sun on the horizon but neither at dawn nor at dusk (i.e. they had made the corresponding differentiation but not the integrations with dawn or dusk). This occurrence is another case of unexpected performance that reinforces the validity and relevance of the constituent elements of the model. Children who ignore the horizon position explain that the sun just goes away, is covered by clouds, is replaced by the moon or goes behind the mountains (suddenly).

Day–night cycle. By age four, all children had made, at some level of explicitness, the necessary differentiations and integrations to distinguish and name night and day (e.g. all could recognize a day scene and a night scene, Figure 3(a) and 3(b)). Spontaneously or upon prompting (question 2), nearly all children mentioned the blue sky (or blue 'clouds') or the light as the telling property; only a few four- and five -year -olds could not explain how they knew, i.e. their knowledge was not yet fully explicit. A large majority knew that daylight is caused by the sun; yet, five children (four to seven years of age) had not made this (causal) integration. Interestingly, 62 out of 70 children stated that the drawing with a light blue sky and the moon (Figure 3(c)) depicts a night scene, and a similar amount that the moon is always out at night—this is a case of erroneous integration of basic differentiations and, therefore, fits well with the model. Yet, none would say that it was night-time if he or she saw the moon in plain day, and none would hesitate that it was night-time even if he or she could not find the moon in the sky. This corroborates the idea that the (concrete) conceptual system is not a direct translation of the perceptual one, but a new and progressively adapted development. It also illustrates how concepts are frequently inconsistent with percepts but the latter are normally favoured in real life situations, particularly in the early phases of said development.

Although this research does not intend to provide quantitative data on the relative frequencies of the different conceptions, it is noteworthy that 55 out of 70 pupils did not sketch the arch trajectory in either direction (and even in the last two grades only 8 out of 20 did), that 39 out of 70 did not know that the sun appears and disappears in the horizon at the beginning and the end of the day (6 out of 20 in the last two grades), and that a majority at all ages believed that the moon is always out at night and never out during the day. This suggests that the teaching of these elementary concepts is failing in many cases and that some educators may be taking for granted certain observational knowledge that numerous students do not possess.

Summary: The experimental data confirm all the predictions made by the diurnal cycle emap. Those results that were unanticipated fit perfectly in the map (all can be constructed with pre-existing differentiations). The development of the most basic (observational) astronomical concepts by Spanish school children appears to be very slow and largely unsuccessful.

Other Findings (Part 2)

As stated, the interviews that were performed for the validation of the emap were followed by clinical interviews that explored issues that were raised during the former. Below I enounce each of the research questions, followed by the proposed explanation.

Why did many children insist that the sun does not move in the sky (i.e. as seen from where we are) and yet drew it all over the sky at different times of the day? Many children insisted that the sun does not move in the sky (i.e. as seen from where we are) and yet drew it all over the sky at different times of the day (see, for example, Figure 7). The resolution of this riddle took several weeks of obsessive work and the elaboration and rejection of several hypotheses until the following explanation was found, which has enriched the model.

In order to differentiate positions of the sun (and therefore to conceive a trajectory), children must dimensionalize the sky first. For as long as this lack of spatial differentiation remains, there is no way to distinguish one place from another; therefore, all are equivalent, and it does not matter where one draws the sun. This phenomenon is somewhat similar to chess squares: as chess rules do not dimensionalize the square, any position within one square is the same position. In this period, drawing the sun in the sky resembles drawing an object in the sea after seeing it from a helicopter that was moving around it.

The vertical dimensionalization seems to be somewhat easier because it has a conspicuous invariant reference point, the horizon, and both directions are asymmetrical due to gravity. In addition, the horizontal dimensionalization is difficult because as the child rotates or changes position, the shape and the direction of possible reference points in the horizon also change. On the other hand, horizontal dimensionalization is taught in school (the cardinal points), whereas the vertical coordinate tends to be overlooked. In fact, a proper dimensionalization and parameterization of the sky is very difficult, even for most adults (see a detailed discussion in Lanciano & Camino, 2008).

For example, in Figure 7(b), the child does not mean that the sun follows such a complicated trajectory; she is being asked to draw the sun again (at other times of the day), so she draws it anywhere; it does not matter where one draws the sun in the sky. Similarly, the child of Figure 6(b) is not proposing that the sun first moves left and then down-right; rather, the sun is up during the day and then goes to the horizon (a half traffic light trajectory). The child in Figure 6(c), instead, has dimensionalized the sky vertically but not horizontally, which is why the drawing looks odd from a horizontal viewpoint but makes sense in the vertical direction (half yo-yo trajectory). In other words, when a child draws the sun in the sky in a random manner—in one or both directions—it may mean one of two things: The child believes (a) that the sun does move quite randomly (e.g. that the sun follows him or her) or (b) that the sun is still, but he or she has not yet dimensionalized the sky in that direction. To distinguish between the two, one must ask whether the sun moves in the sky (in that direction). Only once the sky has been dimensionalized in a certain direction can the differentiation and integration of positions occur. It is conceivable that, on occasion, all three processes happen simultaneously, as may have been the case of a child of only 5:2 who stated that he knows that the sun goes down at dusk because his grandfather showed it to him. Incidentally, this experience highlights the importance of initiating the teaching of concepts directly from observation (of the natural world). The overemphasis on books is illustrated by a boy of seven who said that he knew that there are shadows at night because he had seen a drawing of a man under a street lamp and it had a shadow.

Summary: To conceive a trajectory, children must dimensionalize the sky first.

Why, at all ages, some children state that the sun moves and others state that the sun is still? To answer this question, it must be first noted that both beliefs can be further differentiated as follows. Among those children that state that the sun moves, some believe that it follows them (a well-known conception since Piaget's early work). Although this conception is facilitated by children's egocentrism, it originates from perception, as the sun and moon do seem to follow us, especially when travelling by car. Until this belief is superseded or, in other words, this integration undone (by 'faith' or through the development of implicit projective geometric skills), it is not possible to construct a (cyclical) trajectory. Among children who hold that the sun moves independently of their own movement, the majority believe that it follows a cyclical trajectory (one of those described by the emap), while a few think that it follows a random path, a belief that is not surprising as, throughout the day, one sees the sun randomly left, right, upfront, etc.

Among children who declare that the sun is stationary, one can differentiate those that have learned the heliocentric model and see the movement in the sky as apparent from those who believe that the sun remains stationary in the sky. In addition, some younger children have not even considered the possibility that the sun moves (indeed, the sun appears to be stationary in the sky). At the other extreme, older children may have learned that the sun moves around and along with the galaxy.

Accordingly, the reply to the question of whether the sun moves may oscillate several times throughout development. One possible sequence is as follows: (1) The sun does not move (by default, the sun's movement has not even been considered); (2) the sun moves because it follows me; (3) the sun does not move (it does not follow me, that is an illusion); (4) the sun moves in the sky; (5) the sun does not move; it is the earth that moves; (6) the sun moves around and along with the galaxy. However, the developmental path may be very varied depending on, among other variables, the individual's experiences and, in particular, the school curricula, which frequently teach conception number 5 when the child is still at conception 2 or 3 (leading, presumably, to synthetic conceptions, see Vosniadou, 2012).

Summary: The conception of whether the sun moves evolves through up to six stages.

Why do some children give opposite answers to the same question on different occasions? Throughout the research, there were children that provided opposite answers to the same question when the interview was repeated on a different day. Occasionally, they even switched back and forth between different answers in the same interview (e.g. regarding whether the sun moves). The lack of consistency in children's responses is well known to investigators. Some suggest that it is a methodological artefact, a consequence of children's attempt to provide what the experimenter believes is the right answer or to resolve contradictions *post hoc* as a way to rationalize the response under such extensive probing (see 'Empirical Methodology' section, Part 2, and Siegal et al., 2004; Vosniadou et al., 2004). Others propose that it is also caused by students' daily changes due to learning and maturation (Liu, 2001). Below I discuss two other explanations, which are not exclusionary of the above—in fact, they help explain these, as well as other possible mechanisms.

Contradictory answers may occur because, in the course of development, new models may coexist for some time (or even indefinitely) with those that are being replaced. In other words, while some models become increasingly destabilized (dynamic systems theory) and lose connectivity (cognitive neuroscience, connectionism), the emerging models (generally providing better predictivity or social acceptance) may not have reached sufficient connectivity and stability. Consequently, depending on context and recent experience, children may draw on different portions of their conceptual ecology (diSessa, 2002; Russ et al., 2012) and different models may emerge to consciousness, which may even occur for the first time in the context of the interview. For instance, I asked a child aged six who had drawn a horizontal trajectory if she had ever seen the sun when it gets dark. After a while, she said that it goes down and then proceeded to draw the yo-yo trajectory, while admitting that she had never thought of it (it is interesting that she switched from a totally horizontal trajectory to a totally vertical one). This explanation is consistent with micro-development theories and praxis, which maintain that knowledge structures at different levels coexist and that individuals may operate at different levels depending on context (Granott, 2009). According to Yan and Fischer (2002, p. 142), 'a recent surge of research on micro-development [. . .] has demonstrated the pervasiveness of variability in activity structures, mostly in children'. According to Thelen and Smith (1996, p. 311), 'solutions are always soft assembled, and thus are both constrained by subjects' current intrinsic dynamics and potentially derailed or redirected by task conditions' (however, experts' 'assemblies' should be quite reproducible). Siegler (2002) has proposed replacing the rigid Piagetian stage model (the stair metaphor) by more fluid models such as the overlapping waves metaphor, in which the *probability* of a child using a certain strategy over time has a single-crest wave form that overlaps with other waves.

At a different epistemological level, dynamic systems theory explains variability in cognitive behaviour through nonlinear dynamics (see Yan & Fischer, 2002). Indeed, fluctuation between 'the sun moves because it follows me' and 'the sun does not move' models may occur because the initial conditions, even if they are extremely similar, belong to different basins of attraction (which in many-dimensional systems, such as cognition, tend to be *strange* and their boundaries fractal and, therefore, microscopically intertwined) and typically diverge (sensitive dependence on initial conditions or butterfly effect). In the clinical research, some children switched between the two conceptions depending on unknown and probably subtle variables. Dynamic systems theory allows us to recognize that these fluctuations are not noise, but the form of an underlying structure (two fractal basins of attraction corresponding to conflicting conceptions). Thus, although repeated questioning and varying settings may produce different reactions in the experimental subjects, they are all significant. The more robust (sound and complete) the theoretical lens is, the easier it becomes to assign meaning to these behaviours.

Summary: The not uncommon contradictions and lack of reproducibility in children's responses is informative about inconsistent conceptual structures and not merely experimental noise.

Conclusions

The overall impetus behind this research has been to penetrate children's thought processes in order to find better ways to help them develop their (scientific) minds. More specifically, my objective was to build on the extensive theoretical corpus that grounds the conceptual mind on perception to design a highly amplifying theoretical lens that would allow us to detect 'microscopically' how children develop new concepts in specific areas, in order to design developmentally tiered learning goals and assessment criteria. As described, the resulting emaps model has revealed a well-defined class of misconceptions (rudimental conceptions) and, most importantly, has led to a methodology that maps the development of certain concrete concepts as a web which nodes (the conceptions) are combinations of urelements abstracted from perception. The generative character of its syntax engenders predictions that can be tested experimentally.

The emaps methodology has been applied initially to the diurnal cycle, which has engendered a panoply of conceptions, many of which previously unknown, that have all been identified in children's verbal answers and drawings. Accordingly, these results are strongly supportive of the diurnal cycle emap, and indicate that the emaps methodology can be used to identify and explain the itineraries that children follow in the construction of some conceptual domains. Indeed, the emap for the seasons has already been developed and proven (see summary in Navarro, 2011). Also, this research provides additional evidence that the underlying mechanism of conceptual development, based on differentiation and integration from perception, which was described in the theoretical framework, is real.

The exact limits of the field of validity of emaps have not yet been identified. Emaps consist of simple relations of images (not necessarily visual) that are abstracted from empirical experience, and, therefore, are restricted to some concrete concepts. In the diurnal cycle emap, the urelements are visual images and relations are fundamentally spatio-temporal, but other types are clearly possible, including, for instance, tactile images (e.g. smoothness) or causal relations (e.g. daylight caused by sun). However, as said, not all concrete concepts can be built exclusively with images (e.g. electron, nitrogen). Even when this is the case, it may not be obvious which are the urelements selected by children (see Medin et al., 2000)—thus, empirical testing is generally needed. Furthermore, since the number of possible combinations of urelements increases exponentially, many emaps may just prove unfeasible in practice. Emaps that are developed from non-visual percepts, or a combination of these and visual ones, will be more difficult to verify, since children's conceptions will not be captured through drawings. Also, some concrete concepts are not observational, such as the trajectory of the earth around the sun. The structure and other characteristics of concrete knowledge which learning is mediated by (iconic or symbolic) representations, by need (as above) or by design, is the subject of a separate research.

In addition to enabling said methodology, the emaps framework seems to be a productive theoretical tool, as suggested by the diverse insights that this research has produced about the structure and genesis of the conceptual system. Specifically, the application of the emaps framework in clinical interviews has revealed the, difficult, mental process of dimensionalization of the sky (in line with previous work by Case et al., 1996), has identified a complex developmental itinerary regarding the movement (or not) of the sun, and has provided additional insight about the contradictions and lack of reproducibility in children's responses (related to the coexistence of inconsistent conceptual structures).

Some of the potential applications of the emaps methodology, model and framework to instructional practice are quite immediate—in those domains in which emaps are feasible. The precision and the hierarchical nature of emaps should facilitate the development of more effective learning-goal-driven designs (see Krajcik, McNeill & Reiser, 2008) and tiered assessments linked to development levels (see Caleon & Subramaniam, 2010) for primary education. In fact, emaps methodology has already been used to design the goals and tiered evaluation criteria of a set of teaching units about the diurnal cycle and the annual regularities of the sun's movement in the sky (the seasons), which have been validated experimentally (Navarro, 2011). Furthermore, emaps methodology facilitates the detection of erroneous conceptions, both in general terms and in individual children, provides the structure underlying these conceptions, and pinpoints the architecture of the required conceptual changes, possibly enabling 'precision teaching'. Indeed, the mere drawing of the sun's trajectory reveals which differentiations have not yet been made and which integrations are missing or have not been made correctly (at least not in a stable manner).

This research also suggests that much of the observational knowledge that educators take for granted in the design of primary and secondary school curricula may not have been learned correctly by many students, and that it might be appropriate to reconsider how effectively this early level of the conceptualization of reality is being taught in schools.

Summarily, the available evidence indicates that the emaps framework and methodology provide valuable new insight into both the structure and the genesis of conceptual knowledge, with significant implications for instructional theory and practice.

Notes

1. Although there is not an unambiguous definition of concrete concept, in this paper, it is understood that a concept is concrete (if and) only if it has a referent that occupies anything like a determinate region of spacetime (see Rosen, 2012). In contrast, a concept is herein understood to be observational (if and) only if it can be constructed 'directly' from the observation of nature. For example, the trajectory of the sun in the sky is treated as concrete and observational, whereas the trajectory of the earth around the sun is understood to be concrete but not observational.
2. Some authors, such as Edelman, Lakoff, Llinás, Mounod, and Piaget, highlight the role of motor actions in this process.
3. The binary (order) relation is defined as follows: given two conceptions a and b, $a \leq b$ if and only if b contains all the differentiations of a. This relation has the following properties:
   - $a \leq a$ (reflexivity) for all a;
   - if $a \leq b$ and $b \leq a$ then $a = b$ (a and b contain the same differentiations; antisymmetry);

- if $a \leq b$ and $b \leq c$ then $a \leq c$ (transitivity).
  Therefore, emaps are partially ordered sets. The number of differentiations of *a* conception defines its hierarchical or complexity level.

References

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

Baddeley, A. D. (1999). *Essentials of human memory.* Hove: Psychology Press.

Baxter, J. H. (1989). Children understanding of familiar astronomical beliefs. *International Journal of Science Education*, *11*, 502–513.

Baxter, J. H. (1998). The influences of the national curriculum on children's misconceptions about astronomy. In L. Gouguenheim, D. McNally, & J. R. Percy (Eds.), *New trends in astronomy teaching* (pp. 139–146). IAU Colloquium #162 at the University College London and the Open University, 8–12 July, 1996. Cambridge: Cambridge University Press.

Bernstein, J. H., & Waber, D. P. (2007). Executive capacities from a developmental perspective. In L. Meltzer (Ed.), *Executive function in education: From theory to practice* (pp. 39–54). New York: Guilford.

Bryce, T. G. K., & Blown, E. J. (2006). Cultural mediation of children's cosmologies: A longitudinal study of the astronomy concepts of Chinese and New Zealand children. *International Journal of Science Education*, *28*(10), 1113–1160.

Buty, C., Tiberghien, A., & Le Maréchal, J. F. (2004). Learning hypothesis and an associated tool to analyse teaching-learning sequences. *International Journal of Science Education*, *26*(5), 579–604.

Caleon, I. S., & Subramaniam, R. (2010). Do students know what they know and what they don't know? Using a four-tier diagnostic test to assess the nature of students' alternative conceptions. *Research in Science Education*, *40*(3), 313–337.

Campbell, D. T. (1974). Evolutionary epistemology. In P. A. Schilpp (Ed.), *The philosophy of Karl Popper* (Vol. 1, pp. 412–463). La Salle, IL: Open Court.

Campbell, D. T. (1987). Neurological embodiments of belief and the gap in the fit of phenomena to noumena. In A. Shimony & D. Nails (Eds.), *Naturalistic epistemology: A symposium of two decades* (pp. 165–192). Dordrecht: Reidel.

Case, R., & Mueller, M. P. (2001). Differentiation, integration, and covariance mapping as fundamental processes in cognitive and neurological growth. In J. L. McClelland & R. S. Siegler (Eds.), *Mechanisms of cognitive development: Behavioral and neural perspectives* (pp. 185–252). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Case, R., Stephenson, K. M., Bleiker, C., & Okamoto, Y. (1996). Central spatial structures and their development. In R. Case, Y. Okamoto, S. Griffin, A. McKeough, C. Bleiker, B. Henderson, & K. M. Stephensono (Eds.), *Monographs of the Society for Research in Child Development* (Vol. 61 (1–2), pp. 103–130, Serial No. 246).

Crutch, S. J., & Warrington, E. K. (2005). Abstract and concrete concepts have structurally different representational frameworks. *Brain*, *128*(3), 615–627.

Czico, G. A. (2000). *The things we do: Using the lessons of Bernard and Darwin to understand the what, how, and why of our behavior.* Cambridge, MA: MIT Press.

Damasio, A. (1994/2006). *Descartes' error: Emotion, reason, and the human brain*. London: Vintage.

Demetriou, A., & Raftopoulos, A. (2004). *Cognitive developmental change: Theories, models and measurement*. New York: Cambridge University Press.

Dennett, D. C. (1995/1996). *Darwin's dangerous idea: Evolution and the meanings of life.* London: Penguin.

diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29–60). Dordrecht: Kluwer Academic.

diSessa, A. A. (2007). An interactional analysis of clinical interviewing. *Cognition and Instruction*, *25*(4), 523–565.

Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: A review and analysis. *Studies in Science Education*, *47*(2), 123–182.

Edelman, G. M., & Tononi, G. (2000). *A universe of consciousness: How matter becomes imagination*. New York: Basic Books.

Fischer, K. W. (1980). A theory of cognitive development: The control and construction of hierarchies of skills. *Psychological Review*, *87*(6), 477–531.

Fischer, K. W., & Immordino-Yang, M. H. (2002). Cognitive development and education: From dynamic general structure to specific learning and teaching. In E. Lagemann (Ed.), *Traditions of scholarship in education* (pp. 2–55). Chicago: Spencer Foundation.

Gibbs, R. W. (2010). Embodiment in metaphorical imagination. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thinking* (pp. 65–92). Cambridge: Cambridge University Press.

Gilbert, J. K., Boulter, C. J., & Elmer, R. (2000). Positioning models in science education and in design and technology education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 3–18). Dordrecht: Kluwer Academic.

Goldstone, R. L., & Barsalou, L. W. (1998). Reuniting perception and conception. *Cognition*, *65*(2–3), 231–262.

Goldstone, R. L., Feng, Y., & Rogosky, B. J. (2010). Connecting concepts to each other and the world. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thinking* (pp. 282–314). New York: Cambridge University Press.

Granott, N. (2009). How microdevelopment creates macrodevelopment: Reiterated sequences, backward transitions and the zone of current development. In N. Granott & J. Parziale (Eds.), *Microdevelopment. Transition processes in development and learning* (pp. 213–242). Cambridge: Cambridge University Press.

Harlow, D. B., Swanson, L. H., Nylund-Gibson, K., & Truxler, A. (2011). Using latent class analysis to analyze children's responses to the question "What is a day?". *Science Education*, *95*(3), 477–496.

Hon, G., & Rakover, S. S. (2001). *Explanation: Theoretical approaches and applications*. Dordrecht: Kluwer Academic.

Kaneko, K., & Tsuda, I. (2000). *Complex systems: Chaos and beyond, a constructive approach with applications in life sciences*. Berlin: Springer.

Karmiloff-Smith, A. (1992). *Beyond modularity: A developmental perspective on cognitive science*. Cambridge, MA: MIT Press.

Kikas, E. (1998). The impact of teaching on students' definitions and explanations of astronomical phenomena. *Learning and Instruction*, *8*(5), 439–454.

Knill, D. C., & Pouget, A. (2004). The Bayesian brain: The role of uncertainty in neural coding and computation. *Trends in Neurosciences*, *27*(12), 712–719.

Krajcik, J., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education*, *92*(1), 1–32.

Lakoff, G. (1987). *Women, fire and dangerous things: What categories reveal about the Mind.* Chicago: University of Chicago Press.

Lanciano, N., & Camino, N. (2008). Del ángulo de la geometría a los ángulos en el cielo. Dificultades para la conceptualización de las coordenadas astronómicas acimut y altura [From geometry's angle to the sky's angles. Difficulties for the conceptualization of the astronomical coordinates azimuth and elevation]. *Enseñanza de las Ciencias*, *26*(1), 77–92.

Lawson, A. E. (2010). Basic inferences of scientific reasoning, argumentation, and discovery. *Science Education*, *94*(2), 336–364.

Linn, M. C. (2006). The knowledge integration perspective on learning and instruction. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 242–264). Cambridge: Cambridge University Press.

Liu, X. (2001). Synthesizing research on students' conceptions in science. *International Journal of Science Education*, *23*(1), 55–81.

Llinás, R. R. (2002). *I of the vortex. From neurons to self*. Cambridge, MA: MIT Press.

Mahner, M., & Bunge, M. (1997). *Foundations of biophilosophy*. Berlin: Springer-Verlag.

Mandler, J. M. (1992). How to build a baby: II. Conceptual primitives. *Psychological Review*, *99*, 587–604.

Mandler, J. M., Bauer, P. J., & McDonough, L. (1991). Separating the sheep from the goats: Differentiating global categories. *Cognitive Psychology*, *23*, 263–298.

Medin, D. L., Lynch, E. B., & Solomon, K. O. (2000). Are there kinds of concepts? *Annual Review of Psychology*, *51*, 121–147.

Merleau-Ponty, M. (2002). *Phenomenology of perception*. London: Routledge Classics. Translation of Phénoménologie de la perception (1945). Paris: Gallimard.

Mounod, P. (1993). The emergence of new skills: Dialectic relations between knowledge systems. In G. J. P. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 13–46). Amsterdam: Elsevier Science.

National Research Council. (2007). *Taking science to school: Learning and teaching science in grade K-8*. Washington, DC: The National Academy Press.

Navarro, M. (2011). Enseñanza y aprendizaje de astronomía diurna en primaria mediante "secuencias problematizadas" basadas en el "mapa evolutivo" del tema [Teaching-learning of daytime astronomy in primary education through 'problematized sequences' based on the topic's 'evolutionary map']. *Enseñanza de las Ciencias*, *29*(2), 163–174.

Pecher, D., & Zwaan, R. A. (Eds.). (2010). *Grounding cognition: The role of perception and action in memory, language, and thinking*. New York: Cambridge University Press.

Piaget, J. (1986). *La epistemología genética*. Madrid: Debate. Translation of L'Épistemologie Genetique. (1970). Paris: Presses Universitaires de France.

Piaget, J., & Garcia, R. (1989). *Psychogenesis and the history of science*. New York: Columbia University Press. Translation of Psychogenèse et histoire des sciences. (1983). Paris: Flammarion.

Plummer, J. D. (2009). A cross-age study of children's knowledge of apparent celestial motion. *International Journal of Science Education*, *31*(12), 1571–1605.

Plummer, J. D., & Krajcik, J. (2010). Building a learning progression for celestial motion: Elementary levels from an earth-based perspective. *Journal of Research in Science Teaching*, *47*(7), 768–787.

Popper, K. R. (1972/1979). *Objective knowledge: An evolutionary approach*. New York: Oxford University Press.

Powers, W. T. (1973). *Behavior: The control of perception*. New York: Aldine De Gruyter.

Raftopoulos, A., & Costantinou, C. P. (2004). Types of conceptual change. A dynamical, connectionist account. In A. Demetriou & A. Raftopoulos (Eds.), *Cognitive developmental change: Theories, models, and measurement* (pp. 74–117). Cambridge: Cambridge University Press.

Roald, I., & Mikalsen, O. (2001). Configuration and dynamics of the Earth-Sun-Moon system: An investigation into conceptions of deaf and hearing pupils. *International Journal of Science Education*, *23*, 423–440.

Rosen, G. (2012). Abstract objects. *The Stanford Encyclopedia of Philosophy* (Spring 2012 Edition), E. N. Zalta (Ed.). Retrieved from whttp://plato.stanford.edu/archives/spr2012/entries/abstract-objects/

Ruben, D. H. (1992). *Explaining explanation*. London: Routledge.

Russ, R. S., Lee, V. R., & Sherin, B. L. (2012). Framing in cognitive clinical interviews about intuitive science knowledge: Dynamic student understandings of the discourse interaction. *Science Education*, *96*(4), 573–599.

Sadler, P. M. (1998). Psychometric models of student conceptions in science: Reconciling qualitative studies and distractor-driven assessment instruments. *Journal of Research in Science Teaching*, *35*, 265–296.

Schwartz, M. S., & Fischer, K. W. (2004). Building general knowledge and skill: Cognition and microdevelopment in science learning. In A. Demetriou & A. Raftopoulos (Eds.), *Cognitive developmental change: Theories, models, and measurement* (pp. 157–185). Cambridge: Cambridge University Press.

Scott, P. H., & Driver, R. H. (1998). Learning about science teaching: Perspectives from an action research project. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 67–80). Dordrecht: Kluwer Academic.

Sharp, J., & Kuerbis, P. (2006). Children's ideas about the solar system and the chaos in learning science. *Science Education*, *90*(1), 124–147.

Sherin, B. L., Krakowski, M., & Lee, V. R. (2012). Some assembly required: How scientific explanations are constructed during clinical interviews. *Journal of Research in Science Teaching*, *49*(2), 166–198.

Siegal, M., Butterworth, G., & Newcombe, P. A. (2004). Culture and children's cosmology. *Developmental Science*, *7*(3), 308–324.

Siegler, R. S. (1999). *Emerging minds: The process of change in children's thinking*. New York: Oxford University Press.

Siegler, R. S. (2002). Microgenetic studies of self-explanation. In N. Granott & J. Parziale (Eds.), *Microdevelopment: Transition processes in development and learning* (pp. 31–58). Cambridge: Cambridge University Press.

Siegler, R. S., & Chen, Z. (2008). Differentiation and integration: Guiding principles for analyzing cognitive change. *Developmental Science*, *11*(4), 433–453.

Smith, C. L., Wiser, M., Anderson, C. W., & Krajcik, J. (2006). Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and the atomic molecular theory. *Measurement: Interdisciplinary Research and Perspectives*, *4*(1&2), 1–98.

Thelen, E., & Smith, L. B. (1996). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.

Trumper, R. (2001). A cross age study of junior HS students' conceptions of basic astronomy concepts. *International Journal of Science Education*, *23*(11), 1111–1123.

Varela, F. J. (with Thompson, E. & Rosch, E.). (1991). *The embodied mind: Cognitive science and human experience*. Cambridge, MA: MIT Press.

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

Vosniadou, S. (2012). Reframing the classical approach to conceptual change: Preconceptions, misconceptions and synthetic models. In B. J. Fraser, K. Tobin, & C. McRobbie (Eds.), *Second international handbook of science education, Volume 1* (pp. 119–130). Springer. Retrieved from http://www.springer.com/education+%26+language/science+education/book/978–1–4020-9040-0

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, *24*, 535–585.

Vosniadou, S., & Brewer, W. F. (1994). Mental models of the day/night cycle. *Cognitive Science*, *18*, 123–183.

Vosniadou, S., Skopeliti, I., & Ikospentaki, K. (2004). Modes of knowing and ways of reasoning in elementary astronomy. *Cognitive Development*, *19*(2), 203–222.

Vosniadou, S., Skopeliti, I., & Ikospentak, K. (2005). Reconsidering the role of artifacts in reasoning: Children's understanding of the globe as a model of the earth. *Learning and Instruction*, *15*, 333–351.

Wang, J., Conder, J. A., Blitzer, D. N., & Shinkareva, S. V. (2010). Neural representation of abstract and concrete concepts: A meta-analysis of neuroimaging studies. *Human Brain Mapping*, *31*(10), 1459–1468.

Wilson-Mendenhall, C. D., Simmons, W. K., Martin, A., & Barsalou, L. W. (2013). Contextual processing of abstract concepts reveals neural representations of nonlinguistic semantic content. *Journal of Cognitive Neuroscience*, *25*(6), 920–935.

Yan, Z., & Fischer, K. (2002). Always under construction. Dynamic variations in adult cognitive microdevelopment. *Human Development*, *45*, 141–160.

Appendix

Questions used to analyse the constructs of day and night.

(1) Tell me if it is day or night in this drawing (Figure 3(a)). How do you know?
(2) (If the child mentions that the sun is out) I cannot see the sun in the drawing. How can you tell that it is daytime?
(3) Tell me if it is day or night in this drawing (Figure 3(b)). How do you know?
(4) Tell me if it is day or night in this drawing (Figure 3(c)). How do you know?
(5) (If the child does not mention the sun in question 1) In this drawing, there is a lot of light (Figure 3(a)). Where does this light come from?

(If the child has still not mentioned the sun) Is there always something in the sky when it is daytime?