Young Children's Construction of Operational Definitions in Magnetism: the role of cognitive readiness and scaffolding the learning environment

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Abstract

In this paper, we examine the importance of scaffolding the environment and the role of cognitive readiness in young childrens' construction of operational definitions in magnetism. We discuss various resource constraints and the conceptual background of preschoolers. Then we present an experimental study of 165 children aged 4-6 who took part in an extended structured intervention in which they were guided to construct two operational definitions of a magnet. The two definitions differed with regard to the cognitive demands imposed upon the children attempting to construct them. The construction of the second operational definition required cognitive abilities that the construction of the first did not. Our results demonstrate that children older than 5 years are mostly able to construct both definitions while younger children are able to construct only the first one. Based on this result, we discuss the issue of cognitive readiness and its role in learning. Additionally, by teaching one experimental group of older children the second definition directly and observing their limited success to construct it, we argue for the necessary role of scaffolding the conceptual structure of the curriculum materials to achieve learning.

Introduction

Real understanding of a concept is only demonstrated when children can construct operational definitions (McDermott, 1996). The reason may be that guiding children to formulate such definitions fosters the formation of explicit declarative knowledge, which benefits understanding of the concepts (Peters, et. al., 1999).

A child can be expected to understand those concepts for which the epistemologically prerequisite concepts are manageable and the necessary cognitive resources that will allow concept construction have been acquired. The set of these concepts cannot be determined *a priori* but only through empirical research.

A successful model of teaching should be designed with an eye to the limitations that constrain children's perception and interpretation of the world. It should also seek to take advantage of these limitations by scaffolding the learning environment in ways that enable children to explore their difficulties and to explicitly resolve them.

One of the concepts that have proven recalcitrant to successful teaching is that of magnets. Research (Barrow, 1987; Gagliari, 1981; Selman et. al., 1982) shows that preschoolers notice magnetic attraction but cannot spontaneously offer a successful definition of a magnet. It also shows that they find magnetic repulsion more difficult. Since repulsion is important in differentiating between magnets and non-magnetized ferrous materials, it is important that an understanding of magnets be based on the interactions between two magnets (Gagliari, 1981).

In this paper, we aim to examine the extent to which preschoolers (4-6 years of age) can successfully construct two operational definitions of a magnet. In the first part of the paper, we present the theoretical background regarding preschoolers' representation of the world and the constraints that shape it. We will discuss their intuitive theories of magnetism and will elaborate on the term "cognitive readiness", by which we mean a set of cognitive skills and resources at a given age.Then, we will present a school-based didactic intervention aiming to test whether preschoolers could successfully be taught two different operational definitions of a magnet. The first definition treated magnetism as a substantial property of some objects. The second definition requires that children understand magnetism as a relation between two objects. This, in turn requires, first, that children can combine information from two independent sources, and second, that they can coordinate causal schemes. In this sense, the second definition is cognitively more demanding than the first one. With this approach, we aim to explore the way in which children's cognitive readiness, or lack thereof, manifests itself in the construction of operational definitions of a magnet. Prior to and after the intervention we carried out individual interviews designed to evaluate the children's prior experience with magnets and their ability to apply each of the two definitions.

Theoretical Background

The cognitive basis of intuitive notions of magnetism

One of the basic traits of the preconceptual experiential background, is the tendency of children to believe that properties belong to objects and exist independently of interactions with other bodies. Thus they find it very difficult to comprehend physical concepts that are relational and to represent processes among interacting bodies, such as, electrical or magnetic interactions, gravity or thermal transfer (Carey, 1986; Chi, 1993).

This trait may find its explanation in the fact that preschoolers encode and remember only categorical information (Demetriou *et. al*., 1993; Fisher, 1980), and furthermore, that they fail to encode comparative or contrastive information. Thus, they systematically misrepresent data that contain comparative information (Thelen and Smith, 1994).

The concepts that are based upon our basic interaction with the world have a meaning constituent that is not conceptual but experiential in nature and upon which semantic content is subsequently progressively built. The experiential non-propositional meaning constituent is an image schema (Johnson, 1987). This intuitive, or primitive, meaning is so fundamental that it constitutes the "hard core" of some of our concepts. diSessa (1993) calls such meaning carriers "phenomenological primitives" and they are the main tools that render experience meaningful in the first instance. By virtue of the fact that they are grounded in experience, image schemata are very persistent. This explains the tremendous difficulties we encounter in our effort to revise an image shema, should it prove to be inconsistent with the corresponding scientific concepts. Examples of such schemata are the various image schemata of "force", and pertaining to the topic of this paper, the image of attraction.

In so far as magnetism is concerned, the image schema, or phenomenological primitive, of an attractive force gives rise to the "pulling model" (Erickson, 1994). According to this model the magnet is viewed as an object that has the capability to pull other objects, or, sticks to other objects (Barrow, 1987; Gagliari, 1981; Selman et. al., 1982). This conception of magnetism characterizes the intuitive conceptions of children up to the age of 10.

Children use a wide variety of causal explanations to account for phenomena, and seem to observe both domain-general and domain-specific causal principles. Among the domain general causal principles is the thesis that the causes must resemble their effect - "homeopathy" (Spinger and Keil 1991). With regard to magnetism, this means that it is difficult for young children to grasp a causal mechanism that can lead to disparate and often antithetical effects, as in the case of a magnet that can attract and repel objects. Demetriou et. al. (1993a) argue that children between the ages of 3 and 5 employ proto-causal schemes that allow them to differentiate causal from random sequences on the basis of the structure of events in space and time. Around the age of 5, children can coordinate the proto-causal schemes and search for causes by testing some hypothesis that can be formulated on the basis of the surface structure of the event.

Our discussion thus far reveals the cognitive basis of some of the difficulties that children have with respect to magnets. To recapitulate: (a) children view magnetism as a substantial property of some objects; (b) this property is conceived as the force magnets have in order to pull toward them, or "stick to", other objects; and (c) children find it difficult to understand the fact that a magnet can both attract and repel other objects.

Learning is conditioned upon the epistemological structure of the domain and the cognitive profile of the learner, including the resources that the learning system bears upon the task. Thus, it is important to identify these resources and examine their impact on learning.

Resource limitations and their role in learning

It is now well documented (Kemler 1983; Shepp 1978; Smith and Kemler, 1977) that in classification and discrimination tasks, younger children (up to around 4.5 years of age) tend to perform in a way which suggests that they perceive dimensional combinations as integral, and consequently base their decisions with respect to the classificatory or discriminatory tasks on the perception of the overall similarity of the presented stimuli. Older children classify or discriminate among objects by attending to, and analyzing, the dimensions of the stimuli. This allows them to perceive the embedded structure in the stimuli array. This ability is the decisive factor determining age differences with respect to performance. Further evidence (Gentner and Toupin, 1986; Vosniadou, 1987) suggests that the same maturational trend is attested in tasks of analogy, metaphor, and knowledge transfer.

Another resource limitation is the lack of capacity of children younger than 5 years to combine and integrate information from two independent sources (Halford and McDonald, 1977). They do not have what Piaget calls the capacity to perform logical multiplication. This capacity can influence children's construction of concepts whose definitions require the integration of information.

Resource limitations, far from being a hindrance to learning, render learning possible by scaffolding the environment and the information it feeds to the learning system (Elman, 1991; Raftopoulos, 1997). The key to success lies in effectively limiting the initial access of the cognizer to the full body of information, and in the gradual introduction of the system to the domain's full complexity. This "undersampling" of a complex domain gives the system the opportunity to learn first the domain's features and regularities, and eventually build on them the more complex features which will allow it to generalize.

This conforms with Clark and Thorton's (1997) account of learning, in which problems can be divided into two categories: those whose solution requires finding of the surface structure of the data, that is, first order regularities (type-1), and those whose solution requires finding the deep structure of the data, that is, the more abstract regularities, (type-2 problems). Problems of type-1 can relatively easily be solved by means of an inductive search of the relevant problem space that can extract the basic statistical distributions in the data. Statistical procedure cannot be applied directly to type-2 problems. Thus, problems of type-2 could be solved if transformed to type-1 problems. This can be achieved by recoding and reorganizing the data so that they can render clear the underlying hidden structure. The first operational definition is a typical case of a type-1 problem. It requires that the children limit themselves to examining only information regarding the phenomenon of attraction between bodies. When the first definition is understood, the children "know" that those bodies that can attract others are to be categorized as magnets, all other factors becoming irrelevant to the problem. The property of "attraction" becomes the recoding schema on the basis of which they will attack the second definition, which is a type-2 problem. Once other factors have been eliminated, those children that have the appropriate cognitive readiness include information regarding mutual repulsion and eventually also understand the second operational definition. This is a clear case of undersampling the domain and scaffolding the environment.

In this part of the paper we have discussed certain characteristic developmental trends of preschool aged children, namely, the emergence of the ability to perform logical multiplication, the emergence of the ability to combine proto-causal schemes, and the emergence of the ability to discover embedded structure in an array and go beyond surface similarities. There is also evidence that all these skills appear around the age of 5. Thus, around the age of 5 preschoolers acquire skills that enhance their comprehension of the surrounding world. We will say that these children acquire a "cognitive readiness".

In the next section, we will present an experimental study that was designed in the light of the preceding theoretical framework and aimed to examine the way preschoolers can be quided to comprehend magnetism, by constructing operational definitions of a magnet.

The Experimental Study

The research questions of our study are the following:

(a) can preschoolers learn successfully to construct operational definitions of magnetism?
(b) can preschoolers construct a relational operational definition based on mutual attractions and repulsions, overcoming persistent epistemological obstacles?
(c) is effective scaffolding of the learning environment a necessary condition for preschoolers to construct the second, more complex, operational definition?

Children Participants

The sample included 165 children ranging in age from 3 years and 11 months to 5 years and 7 months (sample mean 4 years and 10 months and standard deviation 6 months). The children attended three kindergartens in a small city and were distributed in six different classrooms. All teachers underwent training in content knowledge, and curriculum implementation procedures.

Description of the teaching intervention

In our intervention, we explicitly encourage children to use evidence (particularly their own observations) to always support their viewpoints. The curriculum materials are very detailed in offering guidance to the teachers as to how to create an environment where children are encouraged to express themselves and every opinion is valued. Some aspects of the curriculum, such as guiding children to classify objects according to material, are not trivial and the activity sequence required many trials before it could be refined to a version that was deemed effective. The unit includes 6 sequential lessons as follows:

1. *Exploring magnets*
2. *Metals and non-metals*
3. *Are all metals attracted by a magnet?*
4. *How can I tell if something is a magnet?*
5. *Magnets with other magnets*
6. *Is there another way to tell if something is a magnet?*

Our interest was in investigating children's ability to construct and apply consistently operational definitions uniquely distinguishing a magnet from other objects. The curriculum guided children to formulate the following operational definitions:

I. Find two objects that do not attract each other. Does your object attract both of them? If yes, then it is a magnet. If not, then try with other objects. (Lesson 4)

II. Find two objects that when approached in some orientation they attract each other AND when approached in another orientation they repel each other. Both of these objects are magnets. (Lesson 6)

The words attraction, orientation and repulsion were usually avoided by the children. Instead they would typically use the words pull, another way, and push, respectively.

Data Collection

The data was collected through individual interviews prior to the intervention, at the end of lesson 4 (Operational Definition I) and in the two weeks following lesson 6 (Operational Definition II).

Task 1: Pretest Interviews

In our initial (pre-test) evaluation, each child was given a bowl with ten objects including 3 magnets and was asked to group them on the basis of interactions between objects. Children were encouraged to settle on one best classification and this was recorded, both photographically and in note form, at the end of the interview. Each classification was then coded based on the criterion that the child seemed to employ.

Task 2: Operational Definition I

In this task, children were presented with a group of 10 objects each of which was hidden in a matchbox wrapped in white paper and sealed with cellotape. This group of hidden objects included only one magnet. Children were explicitly told this and were then asked to give directions to the interviewer so that s/he could identify the magnet. The interviewer acted out the directions so that the child could see the result. All interviews were audiotaped. Children's responses were then coded as a success or a failure based on whether they could provide directions so that the interviewer could apply Operational Definition I consistently.

A set of directions was graded as successful only if it specified all of the following three items:

a) Finding two objects at random that attracted each other,
b) Testing each of the objects repeatedly with a third object;
c) Rejecting one of the two objects that was found not to interact with a third object interacting with the other of the initial two.

Operational Definition II

In this second task, children were presented with a set of 10 identically looking objects wrapped in the same manner as in the first task. They were explicitly told that the objects included two magnets this time and they were asked to give directions to find both magnets in one go. The interviewer again acted out the directions so that the child could see the result. Some children spontaneously resorted to applying operational definition I. When this happened the interviewer clarified once that they were to give one set of directions so that both magnets could be found simultaneously. A response was graded as successful only if it specified all of the following three items:

a) Finding two objects at random that attracted each other,
b) Testing different orientations of the two objects to see of they also repelled
c) Rejecting one object at a time until two objects were found that both attracted and repelled.

Any response that did not include anyone of these items was deemed unsuccessful.

Results

Pre-test interviews

Table 1 presents the results from children's responses in the initial interviews. Many noticed the magnets but ignored them in their groupings. 47 children did not recognize the magnets in their bowls. Most of the groupings were on the basis of colour, shape, heaviness or more than one of these criteria were used simultaneously. The responses of 32 children could not be categorized unambiguously and the criterion is listed as "unidentified".

Table 1: Criteria used by children (N=165) to classify objects in their initial pre-test interviews

Criterion	Number of children
Magnetic attraction	11
Shape	26
Color	32
Heaviness	19
Texture	9
Material	7
Mixed	29
Unidentified	32

118 children appeared to recognize the magnets in their bowls. This number gives an indication of how many of these children remembered having seen a magnet prior to the start of our intervention. Only 11 children noticed that there was a magnet among their objects *and* used it in any way to influence their grouping. This number provides an upper bound on the number of children who may have been able to give an acceptable form of Operational Definition I prior to the intervention. Both, these 11 children and the 32 children who used unidentified criteria were distributed roughly evenly in the 6 classrooms.

Operational Definition Tasks

The total number of children participants is N=165. The number of children who received the whole treatment (lessons 1-6) is N=136. 90.4% (N=123) of these children performed successfully on the Operational Definition I task. Only 47.8% (N=65) of these performed successfully on the Operational Definition II task. Another class of children (N=29) were only examined for Operational Definition II. The success rate for this class was 41.4%.

In order to test the hypothesis on cognitive readiness, we decided to separate the children into three different age groups. Based on our hypothesis we would expect children older than five to perform significantly better on Operational Definition II than children aged below 5. Table 2 presents the children's performance in the two operational definition tasks as a function of age (N=136). The children are divided into three groups according to age (below 4 and 6 months, above 5 and in between). The percentage of children who perform successfully on Operational Definition I is very high. This seems to suggest that after appropriate intervention virtually all children in this age range are able to construct Operational Definition I. Operational Definition II has a substantially lower success rate for every age group. Operational Definition II also demonstrates a strong dependence on age. Only 14.3% below age 4 and 6 months perform successfully. In contrast, 85.4% of children above age 5 are able to consistently construct Operational Definition II.

Table 2: Children's performance on Operational Definitions I and II for different age groups

Group Age Range	N (N_t=136)	Mean Age (yr:mos)	Stand. Devn (mos)	Success rate Opernal Defn I	Success rate Opernal Defn II
> 5	41	5:4	2	95.1%	85.4%
4.5 - 5	46	4:8	2	97.8%	50.0%
< 4.5	49	4:3	2	79.6%	14.3%

We performed a χ^2 test for Operational Definition I: $\chi^2(2) = 10.6$, p<005 (Cramer's coefficient ϕ=0.28, p<.01, N=136). This result indicates that children's performance on Operational Definition I statistically depends on age. The test with Operational Definition II gave the following result: $\chi^2(2)$=45.3, p<.000 (Cramer's coefficient ϕ=0.58, p<.005, N=136). The Cramer coefficient indicates that performance on Operational Definition I is only weakly associated with age. In contrast, performance on Operational Definition II and age show a moderate to strong association. The difference between these two Cramer coefficients is statistically significant (t=3.44. p<.001) (Howell, 1997).

Relative Demands of Operational Definitions I and II. Table 3 shows the number of children that succeeded or failed in either of the two operational definition tasks. Only 9% (N=12) of the children failed both tasks. Forty-seven percent (N=64) of the children succeeded on both tasks. These values testify to the effectiveness of the teaching intervention. Forty-three percent (N=59) of the children succeeded in Operational Definition I and failed in II. In contrast, only 1 child succeeded in Operational Definition II and failed in I. These findings support the sequencing of our curriculum by indicating that Operational Definition II (Lesson 6) is more demanding than Operational Definition I (Lesson 4).

Table 3: Children's performance on Operational Definitions

	Operational Definition I	
Operational Definition II	Failure	Success
Failure	12	59
Success	1	64

To confirm this finding we carried out McNemar's test for the significance of change on the sample of children that were taught all 6 lessons (N=136): $\chi^2(1)$=54.2, p=.000. The result clearly confirms that Operational Definition II is significantly more difficult than Operational Definition I.

Tables 2 and 3 do not include the performance of children in class 5 because this class received the modified intervention (lessons 1-3, 5, 6) and was only tested for Operational Definition II. Class 5 and the group of children listed in Table 2 with age higher than 5 years have very similar average ages. The t-test between these two groups shows that the difference in mean age is not statistically significant. In other words, class 5 is matched to the group of older children in Table 2 in age (t(38)=-0.6, p>.5). Only 41.3% of the children in class 5 performed successfully in Operational Definition II. In comparison with 85.4% success rate for the older children in Table 2, this is appreciably lower. The children in class 5 performed closer to the 4.5–5 year olds rather than the >5 year olds. The χ^2 test for Operational Definition II ($\chi^2(1)$=13.8, p<.005) indicates that there is a statistically significant difference in the performance of class 5 and the older group of children who received the complete intervention. Not teaching lesson 4 and Operational Definition I seems to have influenced these children's performance on Operational Definition II significantly. This would indicate that to some extent Operational Definition I (and lesson 4) functions as a conceptual pre-requisite to successful performance on the Operational Definition II task.

Discussion

It is evident that even though the children across all ages could not initially categorize magnets, the appropriate didactic intervention led them to construct the first operational definition. Our study shows that 79.6% of the first age group, 97.8% of the second age group, and 95.1% of the third group succeeded in constructing the first operational definition.

The nature of the first definition explains the success rate across all ages. Some objects attract others, whereas some other objects do not. Attraction was the only factor to be taken into account. The definition could be constructed by using information from one source only and did not clash with children's conception of magnetism as a substantial property and with their view of causality as an homeopathy. Additionally, it was consistent with the image schema of attracting force and the pulling model.

Only 14.3% of the first group could construct Operational Definition II. In contrast, fifty percent of the second group and 85.4% of the third group succeed in the task. Thus, only children older than 5 years of age succeed. Almost all younger children fail.

In the second definition, some objects sometimes attract and sometimes repel other objects. In this case, there are two factors to be taken into account and the information must be combined for successful categorization. Thus, children who cannot perform logical multiplication are unable to understand it. Magnetism is seen, now, as the result of an interaction between bodies and not necessarily as a property that an object may have by itself. This is a second reason that makes it more difficult for the younger children to succeed. The phenomenon of repulsion further complicates matters. Homeopathy seems to be violated, since the same object can attract and repel other objects. The causal patterns that can explain the phenomenon become more complex.

Children over 5 years of age, having mostly acquired the skill of logical multiplication and being able to coordinate causal schemes, can benefit from instruction and are ready to construct the second definition. We do not claim that the children who succeed, understand the relational nature of magnetism. The fact still remains that a necessary step toward accomplishing this has been undertaken that will allow them to overcome the epistemological obstacle of conceiving all physical properties as substantial properties of matter.

We have elaborated on the crucial issue of scaffolding the learning environment, and argued that successful learning requires that the learner does not process the full complexity of the problem from the beginning. The learning system has the opportunity to learn first the domain's basic features and regularities. These provide the learning system with a code that will allow it to recode the information pertaining to the complex problem.

Children who are cognitively ready (older than 5 years of age) and have been trained with appropriately scaffolded material are expected to exhibit a markedly different performance pattern. To test this, we bypassed lesson four and the first operational definition with a group of 29 students, proceeding directly to the second operational definition. The study shows that only 41,4% succeeded in constructing the second definition, in comparison with 85.4% of the preschoolers of the same age (the third group). Our study, thus, confirms the decisive role of diminishing the cognitive load that the learner initially faces.

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