Semiotic multiplicities and contradictions in science learning

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ABSTRACT

In this paper, we explore the notion of situated and modally defined learning, aiming to identify and describe action structures as thought structures. Our focus is on investigating modal patterns that emerge during the learning process, using a case study involving a 5-year-old preschool child's conceptualization of mechanical equilibrium. To achieve this, we designed three identical tests, each eliciting different modal responses from the student. These tests comprised three tasks that varied semiotically. They were administered at different time points and interspersed with two distinct teaching interventions. The findings revealed that during the conceptualization of mechanical equilibrium, the student displayed semiotic multiplicities, employing various modalities and semiotic systems to represent the same conceptual dimensions of the phenomenon. Interestingly, the student's thinking exhibited regressions between compatible and non-compatible conceptualizations in line with school knowledge, leading to apparent contradictions. These observations highlight the concept of variability and underscore how multiplicities and contradictions are integral components of the dynamic learning process.

KEYWORDS

Science education, mechanical equilibrium, semiotic multiplicities, semiotic contradictions, science learning

RÉSUMÉ

Dans cet article, nous explorons la notion d'apprentissage situé et défini modalement, dans le but d'identifier et de décrire les structures d'action en tant que structures de la pensée. Notre attention se porte sur l'investigation des schémas modaux qui émergent lors du processus d'apprentissage, en utilisant une étude de cas impliquant la conceptualisation de l'équilibre mécanique par un enfant de 5 ans en maternelle. Pour ce faire, nous avons conçu trois tests identiques, chacun suscitant des réponses modales différentes de l'élève. Ces tests comprenaient trois tâches variant sur le plan sémiotique. Ils ont été administrés à différents moments et entrecoupés de deux interventions pédagogiques distinctes. Les résultats ont révélé que lors de la conceptualisation de l'équilibre mécanique, l'élève présentait des multiplicités sémiotiques, utilisant diverses modalités et systèmes sémiotiques pour représenter les mêmes dimensions conceptuelles du phénomène. De manière intéressante, la pensée de l'élève a montré des régressions entre des conceptualisations compatibles et non compatibles avec les connaissances scolaires, conduisant à des contradictions apparentes. Ces observations mettent en lumière le concept de variabilité et soulignent comment les multiplicités et les contradictions sont des composantes intégrales du processus d'apprentissage dynamique.

MOTS–CLÉS

Éducation scientifique, équilibre mécanique, multiplicités sémiotiques, contradictions sémiotiques, apprentissage des sciences

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INTRODUCTION

Concepts embody properties derived from the context in which they are formed (Garbarini & Adenzato, 2004; Shapiro, 2019; Varela et al., 1991). This association aligns with the pragmatic dimension of ideas, as human engagement with the material world expands cognition beyond internal processes into external environments (Adam & Galinsky, 2012; Wilson & Golonka, 2013). Human thought integrates with actions, assuming that concepts are linked to the reception of information from the environment and the human sensorimotor system. Notably, meaning construction is associated with systems related to human senses and movements in space (Beilock et al., 2008; Kontra et al., 2012). In that sense, mental representations acquire tangible referents through human engagement in the physical world, thereby alleviating the inherent level of abstraction associated with the abstract realm of ideas and rendering it concrete and specific (Lakoff & Johnson, 1999). In fact, thinking and action are inseparable and mutually influential as stated by Merleau-Ponty (2004), who emphasizes the interconnectedness of our perception and understanding of the world with the integrated nature of the human body.

In education, learning is seen as action based, with knowledge defined through students' actions (Dewey, 1938). Recently, the fields of science education, mathematics education, and ICT or robotics in education are systematically researching this (Han, 2013; Pantidos & Givry, 2021; Roth & Welzel, 2001; Zacharia & Olympiou, 2011). Typical methodologies studying the formation of scientific concepts in educational contexts support the action-based hypothesis recognizing that changes in students' action demonstrate cognitive construction and improvement. When students speak, they can also use gestures, which frequently clarify speech, since what they show or depict can either complement or even oppose the information conveyed verbally (Herakleioti & Pantidos, 2016). The same might occur with the explanation they provide for their drawings, since the drawing itself might provide us with one explanation, their speech with another, and any gestures the students might use to explain their drawings with yet another (Chang 2012; Einarsdottir et al., 2009).

Embodied learning, especially, has received considerable research attention in the field of early childhood science education. Teaching methodologies consider the evolution of scientific understanding through students' activities in their social, cultural, and historical context (Fragkiadaki et al., 2019; Roth et al., 2012). In a project on the phenomenon of earthquake creation involving preschoolers, Chachlioutaki et al. (2016) demonstrated in a pre/posttest research process that, when children develop their semiotic modes, they also develop their reasoning regarding the conceptual dimensions of the phenomenon, while in many cases the human body and drawings conveyed meanings regarding the place earthquakes were created and the movement of lithospheric plates that speech had been unable to conceptualize. Even for phenomena in the microcosm, such as the particle nature of matter and the link between temperature and the movement of molecules, the students' physical involvement leads to improvements in learning (Hadzigeorgiou, 2002). Actually, for preschoolers embodied thinking constitutes a type of disguised cognition, since children sometimes prefer to think exclusively with their body, something that does not prosper when the semiotic context does not encourage bodily expression.

In summary, it can be argued that the various approaches developed over time, such as situated cognition, distributed cognition, and embodied cognition, share a common underlying principle. They all link learning to the actions and experiences that take place in the tangible world, including the virtual realm, while being deeply rooted within the social, cultural, and physical context in which they originate and develop (Clark & Chalmers, 1998; Shapiro, 2019). This research explores expressive patterns in learning and their influence on preschool students' understanding of mechanical equilibrium. Previous studies have examined reasoning development in mechanical equilibrium, categorizing students' evolution from intuitive choices to causal explanations (Hardiman et al., 1986; Inhelder & Piaget, 1958; Siegler & Klahr, 1982). The semiotic context of mechanical equilibrium, mostly focused on physical balance, has been explored (Ortiz et al., 2005; Sarıoğlan & Küçüközer, 2014), along with the kinesthetic perception of equilibrium (Hadzigeorgiou et al., 2009). The current paper relies on a case study aiming to identify the modalities of speech, drawing, and bodily expression used by a preschooler and their associations with the conceptualization of mechanical equilibrium.

METHODOLOGICAL FRAMEWORK

Research design

The case study encompasses a five-year-old child from an urban public kindergarten who had no prior learning experience within the school context regarding the phenomenon of mechanical equilibrium. Different semiotic conditions were created to explore the conceptual dimensions of mechanical equilibrium, focusing on beam equilibrium with equal and unequal weights. The aim was to encourage the child's thought patterns through various expressive modes. The study acknowledges that the student's choice of modes and their interactions contribute to learning and recognizes the significant impact of the semiotic context in a learning environment.

The study employed two types of effects: semi-structured interview/test and teaching interventions. The interview consisted of three tasks with different semiotic variations, including oral questions (task 1), drawing activities (task 2), and manipulation of a mathematical balance (task 3). The purpose was to elicit unambiguous effects rather than exact repetition of previous ideas. The teaching interventions involved a simulation of mechanical equilibrium (https://phet.colorado.edu/sims/html/balancing-act/latest/balancing-act_en.html) and a physical seesaw, each with its distinct semiotic context. The seesaw allowed the child to climb it and attempt to balance using various weights, thus exploring the dimensions of the phenomenon. The simulation includes a human–intangible entities interaction, while the seesaw a human–material objects interaction. The interview was conducted three times: once before the simulation intervention, once between the two interventions, and once after the physical seesaw intervention. The interventions were spaced ten days apart.

Data collection

The three test tasks were recorded to collect data at different time points. Each task presented the student with a specific position of a material object related to the conceptual dimensions of mechanical equilibrium. The first task involved verbal expressions, while the second task required the student to draw an object on a seesaw. In the third task, the student interacted with a mathematical balance. All tasks included questions about placing another object on the seesaw, with different data used for each task, tailored to the specific context.

The dimension of equal weights (D1) was divided into two sub-dimensions. In D1a, the given object was positioned at one end of the seesaw/balance, and the student had to determine where an object of the same weight should be placed to achieve balance, providing an explanation. In D1b, the given object was moved slightly inward, and the student was asked to identify the placement of the other object providing explanations. The dimension of unequal weights (D2) was similarly divided into D2a and D2b, with different placements of the given object. Questions were also included where the given object weighed twice as much, requiring the student to indicate where a lighter object should be placed to restore equilibrium.

In the first task, the student provided oral responses and gestures, while the second task involved drawing, verbal explanations and gestures. The third task involved answering questions about balancing equal and unequal weights on the mathematical balance. Data collected in this task consisted of the student's speech and bodily expressions, as gestures were used to indicate the appropriate hanging point for each weight. Eventually, data were collected from the student's speech, gestures, and drawings (Chachlioutaki et al., 2016). Modalities were categorized as speech (s_i), bodily expressions (deictic gestures - dg_i, iconic gestures - ig_i, ergotic gestures - eg_i), and drawing (d_i). Gestures pointing in one direction (usually with the index finger) are deictic, those that morphologically depict a human activity or an (in)animate entity are iconic, while ergotic gestures are associated with wielding material objects (Roth, 2003). Coding decisions were based on conceptual criteria, assigning codes to words and phrases important for meaning production. The compatibility of modalities with scientific knowledge was evaluated, and correct responses were labeled. The coding process involved independent coding by each author and collaborative sessions for agreement (Givry & Roth, 2006). Cases without agreement were excluded (less than 1% of data).

Although the tasks had different formats, equivalent questions regarding equal and unequal weights were asked in each task. This approach allowed the researchers to repeat the same questions three times, adapting them to the specific contexts, resulting in a comprehensive dataset while maintaining consistency.

Data analysis

The key in Table 1, allows us to assign a piece of meaning to each modality. Furthermore, it also records the semiotic system the modalities are derived from.

TABLE 1

Modalities and pieces of meaning

Referent	Key concepts	Signifiers (modes)
Balancing equal weights (DI)	same weight + same position on the other side	si, igi, dgi, egi, di
Balancing unequal weights (D2)	heavy object + inner position = light object + outer position	si + igi, dgi,+si, di et.

The Referent column shows the conceptual dimension of mechanical equilibrium the student is referring to, i.e., "what she/he refers to". The second column, Key Concepts, states the crucial concepts the student's reasoning must include to be complete for each conceptual dimension DI and D2. For D2 the "+" symbol distinguishes one crucial concept from the other, indicating that the two concepts are complementary. The third column, Signifiers (Modes), contains the codification of the empirical data, i.e., what the student actually said and did, using speech, gestures, and drawings. In this way, the distinct pieces of meaning each modality carried were recorded, along with how modalities of different semiotic systems collaborate.

During each test, the student was questioned about each conceptual dimension (DI and D2) three times, by means of the three tasks. This was repeated three times, i.e., in three tests. This means that the student was questioned 3*3=9 times about each dimension DI and D2. In each test, the child was questioned in three morphologically different contexts/tasks (i.e., speech, drawing, mathematical balance). Therefore, all in all, the same or equivalent question was put to the student nine times, resulting in the researchers receiving at least nine responses. Thus, with the key from Table I, all the child's responses were found for the nine times it was asked about the same referent, i.e., the same conceptual dimension. This is how we explored how the same meaning is communicated through different semiotic systems as well as through the same semiotic system (Ist axis of analysis).

Furthermore, each modality was semantically evaluated on the basis of how scientifically compatible it was. As a result, it was possible to record the sequences of correct/incorrect thought acts as responses to the "same" question (2nd axis of analysis).

RESULTS

It is reminded that the questions posed to the student assumed one aspect of the equilibrium condition, leaving the other part for the student to determine. For instance, in task 3, one of the questions already had a weight hanging from the balance, and the student had to identify where another weight should be placed to achieve balance. In task 1, when dealing with unequal weights, the teacher would instruct the student to imagine sitting on a seesaw and ask where they should sit to balance it. It is important to note that each task, specifically for unequal weights, provided either the heavy or light object as a given, ensuring that the student's responses incorporated the corresponding reasoning based on the case. The results presented below encompass the student's expressions, including where they were expressed.

Semiotic multiplicities

As mentioned, the first axis of analysis recorded the sum total of the different modal expressions the student employed for each of the two conceptual dimensions of mechanical equilibrium. In other words, we examined how the student responded to the same/equivalent questions in each test and each task. For balancing equal weights (D1) the semiotic multiplicity for "same weights" is three (3) and for "same position" four (4) (see Table 2). The student conceptualizes the same weight using speech, an iconic gesture, as well by drawing, while the same position is also expressed with a drawing and through one iconic and two deictic gestures. Note that modality d_1 signifies both the key concept of same weight and the same position, since, once drawn, d_1, contains two pieces of information. Size indicates the same weight—this was agreed after student's suggestion—while the point where it is placed indicates position on the balance. Correspondingly, gesture ig_1 simultaneously indicates that two objects (hands) of equal size (and equal weight) must be placed in symmetrical positions for the seesaw to balance. Keep in mind that for equal weights to balance, the correct conceptualization is: For the seesaw to balance, the equal weights must be at the same distance from its center (or in terms of visual symmetry in corresponding positions).

TABLE 2

Modalities that conceptualized dimension D1

	Same weight	**Same position on the other side**
Balancing equal weights (D1)	s_1 d_1 ig1	d_1 ig_1, dg_1, dg_2

s_1: "same kilos", d_1: "draws a square of equal size at one end" (an identical square already existed at the other end), ig_1: "opens his/her arms wide, hands facing each other", dg_1: "points to the right or left end of the balance, dg_2: "point a little further in from the left or right end of the balance"

For balancing unequal weights (D2) the semiotic multiplicity is five (5) for "heavy object", three (3) for "light object", five (5) for "inner position", and three (3) for "outer position" (See Table 3).

Table 3

Modalities that conceptualized dimension D2

	Heavy object	Inner position	Light object	Outer position
Balancing equal weights (D2)	s_5, s_2 d_2 dg_6, dg_4	s_3 d_2 dg_3, dg_6, dg_4	s_6, s_4 dg_5	s_8 dg_1, dg_5

s_5: "you", s_2: "large", s_6: "I", s_4: "small", s_3: "in", s_8: "out", d_2: "draws the heavy brick near the approximate center of the right side"|, dg_5: "points to the light brick he/she has drawn", dg_6: "points to the heavy brick he/she has drawn", dg_3: "points to the center of the balance", dg_1: "points to the right or left end of the balance", dg_4: "points to the two bricks in the center of the left side".

The student conceptualizes the heavy object by uttering two different words, drawing the object at one position, and using two deictic gestures. Correspondingly, the student conceptualizes the light object using two different words and one deictic gesture. It should be noted that the deictic gestures dg_6, dg_4 and dg_5 do not conceptualize autonomously the entities "heavy object", "light object", "inner position" or "outer position". In other words, they point to something that has already been conceptualized and preexists in physical space. For example, in task 2, the student first draws a brick, and then points to it. So, the student first conceptualizes the heavy object through d_2 and then underline the meaning by pointing to the brick through dg_6. Specifically, these deictic gestures point either to an object that has already been drawn and denotes "light" (dg_5) or "heavy" (dg_6), or to the bricks that have already been placed on the mathematical balance (dg_4). However, they are recorded as multiplicities since bodily deixis plays an important role in the process of generating reasoning, because it connects the "immaterial" spoken word with the material presentation (Thompson & Massaro, 1994).

For inner position, the student uses speech, draws the object at one position and uses three deictic gestures, while for outer position, the student uses speech and two deictic gestures. Note that modality d_2 signifies both key concepts of heavy object and inner position, because as in dimension D1 once drawn they carry two pieces of information. In other words, by design, the larger size denotes the heavier object, while the point where it is placed denotes its position on the balance. The convention that a large size denotes greater weight and vice versa was agreed upon from the beginning and was the student's idea and proposal. For balancing unequal weights, the correct conceptualization is that for the seesaw to balance, the heavier object must be at an inner position on the seesaw/balance with the lighter object at an outer position.

Semiotic contradictions

Based on the second axis of analysis, Table 4 shows the student's responses/explanations regarding the dimensions of equal and unequal weights, which create sequences of correct/incorrect conceptualizations. As reported, the two researchers characterized the child's modal "sentences" as correct or false according to how scientifically compatible they were. Hence, a series of contradictions was recorded. For example, in one case, the student, while initially drawing the weight at the correct spot and explaining why it would level the seesaw in that position, at a later, different test his/her drawing and response were false.

TABLE 4

Series of contradictions between correct and false responses

	Test 1						Test 2						Test 3					
	Task1		Task2		Task3		Task1		Task2		Task3		Task1		Task2		Task3	
D1	F	F			C	F	C	F	C		F	C	F	F	F	F	C	C
D2	F	F	F	F	F	F	C	C	C		F		C	F	C	F	C	C

This creates a profile with semantic contradictions over time. A blank cell indicates the student did not respond.

DISCUSSION

The student exhibited semiotic multiplicities for both dimensions, i.e., the student expressed the same meanings with all the semiotic systems as well as with different modalities within the same semiotic system. According to Givry and Roth (2006) expressive pluralism for the same meaning is an indication of conceptual evolution. Multiplicity is not repetition but a kind of transformation associated with human cognition. Different gestures, speech, or a drawing might have the same referent, but the ability to exhibit different modalities for a spatial entity is an indicator of development of student's spatial intelligence (Goodchild & Janelle, 2010; Hegarty, 2010). Actually, the student generated the appropriate modalities for each specific task. In addition, using different modalities for the same concept indicates that individual is capable of adjusting his/her thinking to various contexts. This suggests that his/her knowledge becomes more cohesive, as it can be transferred and applied to different situations (Prain & Waldrip, 2006). It is worth noting that the contribution of transfer knowledge across modalities to the improvement of an agent's performance is the subject of research on biological organisms in general as well as on artificial cognitive systems (Orabona et al., 2009; Yildirim & Jacobs, 2013).

In current research, even the production of two different deictic gestures (i.e., deixis to two points on the balance at two different time points) is an indication that the student can apply the rule of equal weights to different positions on the balance. In other words, simple deixis, when applied multiple times as the response to the same, or equivalent, question, might serve as confirmation that the student is following specific cognitive processes, which are associated with running a rule, and not simply making a random choice, something that might be covered up by the use of a single deictic gesture or, more generally a single modality. This conclusion is exaggerated by the multiplicity of expression the student demonstrates, not only through deictic gestures but also through the other modalities of speech and space he/she employed. Even the deictic gestures pointing to something that already exists as a material entity in space are also important; such deictic gestures are dg_5, dg_6 and dg_4, which point to something that has already been drawn (task 2) or material bricks (task 3). Indeed, research on human cognition has demonstrated that deictic gestures unify the meaning-making process, interconnecting the frequently ambivalent references of speech with the unambiguous material entities of the environment (Thompson & Massaro, 1994). We should note here that research into the collaboration of deictic gestures with speech is also the subject of research in fields such as human-animal interaction and cognitive robotics (Lakatos et al., 2012; Pizzuto & Cangelosi, 2019).

Finally, the student presented regressions between correct and incorrect answers regarding the dimensions of balancing equal and unequal weights (see Table 4). These contradictions refer to the conceptual content of the modalities the student employed and appeared not only during the same test but also in the same tasks during different tests. Namely, at some point in time, the student answered correctly and, at a later time, answered an equivalent question incorrectly and vice versa. In addition, when faced with equivalent questions in different semiotic contexts (e.g. speech, drawing activity) the student presented corresponding regressions. It appears that the student presented knowledge inconsistency at different time points, something that might be attributed, as mentioned above, to the effect of each task/semiotic context each time. In cognitive sciences the creation of a sequence of conceptualizations that are both compatible and incompatible with what is scientifically acceptable, i.e., knowledge variability and knowledge inconsistency, refers to learning, and more specifically to transitional knowledge and decision making (Church, 1999). For example, mismatches between speech and gestures constitute predictors of learning, leading to the emergence of language and, generally, cognitive growth (Goldin-Meadow, 2017). Similarly, conflicting opinions, choices, assumptions, or ideas can constitute crucial heuristics in decision making (Zhang & Grégoire, 2011). Consequently, a sound theorization emerging from our research might be that regressions between the correct and incorrect answers the student presented constitute a condition of learning. Namely, the student appears to be in a dynamic process of redefinition and readjustment. Naturally, this particular research does not confirm the above hypothesis, but, as mentioned, research in cognitive sciences in other contexts, documents the contribution of contradictions to the learning process. Further and deeper analysis from our data is required to confirm the specific hypothesis, as well as to investigate a possible correlation of the tasks' semiotic variability and the modalities the student employed with the pattern of his/her correct-incorrect responses. Additionally, general issues related to science teaching and learning come to the forefront. For example, the mismatches between students' bodily expression and speech, the students' realization of the contradictory conceptualizations carried by different modalities in a given context, and the design of teaching activities that promote semantic contradictions by activating different modalities are matters requiring further research.

Since this particular research is a case study, we have no intention of generalizing from it. Nevertheless, from the in-depth examination of the student's thinking in relation to the modalities used in various semiotic contexts, the modal patterns recorded could be characterized as learning structures. Semiotic multiplicities and modalities that present inconsistencies serve the concept of variability in thinking, which the cognitive sciences have found particularly valuable for several decades (Ping et al., 2021), enters the field of science education and obviously must be explored further.

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