

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

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Motor Skills, Creativity, and Cognition in Learning Physics Concepts

SYNOPSIS

Both ethnographic and neuroscientific research suggest that physicists solve problems by engaging in imaginary sensorimotor simulation of phenomena under inquiry. However, how this finding might inform high-school instructional practice is yet unknown. As educational researchers who are inspired by embodiment theory, we are investigating the potential roles that students' choreographed physical movements in classroom space play in learning physics concepts related to motion. Here we focus on two case studies of high-school students whose summative projects for an instructional unit involving movement-based problem solving manifested deep conceptual and affective relations with the subject matter. Through qualitative analyses we attempt to build a coherent narrative of the subjective processes that led to these results.

INTRODUCTION

How can one support students in establishing relationships between their naturally developed spontaneous conceptions and the scientific conceptions learnt in school? In other words, what is the connection between naïve knowledge and disciplinary knowledge such as mechanics concepts in physics? Many studies on students' learning of mechanics, at all levels of schooling, show that students experience difficulties in comprehending concepts in this domain, often forming alternative conceptions that are based on intuitive knowledge and are incongruent with normative conceptions of physics (1).

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

Physics educators have advocated active learning, beyond mere lecturing, as a method for connecting naïve and disciplinary knowledge (2). Hake (3), for example, examined pre- and post-test data for more than 6,000 students in introductory physics courses and found significantly improved performance for students in classes with substantial use of interactive engagement methods involving active learning. Test scores measuring conceptual understanding were roughly twice as high in classes promoting engagement than in traditional courses.

One approach for connecting experience with conceptual knowledge is ‘embodiment’ a cognitive science paradigm that rejects philosophical dissociations of brain and body. According to this approach, the mind is an activity distributed over the body, the environment, society, and culture (4). Yet whereas theorists of embodied cognition seek to position sensorimotor activity as formative of all reasoning, *“there is limited agreement on what the term "embodied cognition" exactly means and to what extent "embodiment" includes sensorimotor versus higher level cognitive function”*, p.513 (5). Almost a century ago, though, the Soviet cultural–historical psychologist Lev Vygotsky already made strides in articulating the inherent sensorimotor quality of reasoning: *“Every thought associated with movement induces on its own a certain preliminary straining of a corresponding muscular system that tends to be expressed in movement. If it remains only a thought, then since this movement is not brought to fruition and is not disclosed, it remains concealed in an entirely tangible and effectual form“*, p. 161 (6).

Educational researchers informed by embodiment theory have been building and evaluating learning environments that create opportunities for students to engage in sensorimotor problem solving as a pedagogical means of supporting conceptual

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

development (7). For example, Abrahamson and Trninic (8) report on a study in which embodiment theory inspired an educational design for the mathematical concept of proportional equivalence. Similarly, Scherr and collaborators have been researching a design for the physics concept of energy (9, 10). In these and other studies the role of multimodality, such as manual gesturing, has been theorized as important in mediating action, reasoning, and discourse (11-13).

Educational research on embodiment, and in particular the more encompassing view of the mind, has interfaced with critical-pedagogy literature looking to expand our conceptualization of where and how learning transpires. For example, some researchers have looked to characterize *hybrid learning environments* that bridge home and community practices, identities, and experiences with school practices (14). In designing a productive hybridity one needs “*to ensure that ongoing emergent hybrid practices are guided in ways that promote disciplinary learning goals*”, p. 338 (15). In the present study, a dance studio was used as a hybrid environment for embodied learning.

EMBODIED PEDAGOGY IN THIS STUDY

In this article we describe two case studies of 10th grade high-school students learning the complicated physics concepts of balance and angular velocity. The students participated in a physics course based on the embodied pedagogy described below. The case studies track the students’ experiences throughout the course, culminating with their summative projects. The summative projects were delivered in a variety of modalities, such as video art, music, and dance. As we will report, the projects manifested deep conceptual and affective relations with the learnt material.

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

The learning activities in this study were based on the embodied design heuristic **‘Experience first, signify later’** (7, 16). That is, the rationale for the proposed design was that students might experience important opportunities to make sense of physics concepts by means of: A. participating in activities in which they themselves enact these concepts; and then B. reflecting on the experiences and signifying them within the semiotic register of the physics disciplinary field. In this study, students worked either individually, in pairs, or collectively on a choreographic task that gave rise to problems of coordinating movements. Solving and expressing these solutions, we argue, created significant learning opportunities.

Zohar, Bagno, and Eylon (17) articulated the following components of an embodied pedagogy for science concepts:

A. **Directed bodily experiences** that act as a resource enabling the learner to relate complex (often abstract) ideas in physics to the learner’s everyday experiences. These **‘Informed Movements’** (18) are designed to enhance students’ visualization of a new idea as well as its analysis, expression, and actualization. One example is the “collective circular activity” described in the case study of learning angular velocity (see below).

B. **Improvisation in movement** mediates between imaginative reasoning, body actions, and feelings, as shown in Fig. 1. How this mediation is carried out is described in the case studies below.

Motor Skills, Creativity, and Cognition in Learning Physics Concepts



Fig. 1: An example of improvisation in movement, a component of the embodied pedagogy.

C. **Techniques combining walking with talking** (19). For example, following an improvisation involving circular movements with different parts of the body, students are asked to walk in the studio and think to themselves about circular movements in real life and nature. Then, the students talk with each other about their answers and share ideas with the plenum.

D. **Selected aspects of the Feldenkrais method** (20) intended to increase body awareness and emphasize its connection with physical phenomena. For example in the balance case study we used Feldenkrais exercises related to the issue of stability.

E. **Relaxation**, for example lying on the floor and using belly breathing as shown in Fig. 2.



Fig. 2: An example of relaxation, a component of the embodied pedagogy.

The first author acted as the instructor for the lessons described in this paper. Videography of the activities in the case studies was analyzed to track for the emergence

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

and establishment of multimodal actions and utterance that, we conjecture, serves to ground the curricular content in physical movement. We argue that our narratives document individual contributions to, and evolutions through, a classroom sociogenesis of new semiotic bundles, where conceptual meanings are collectively grounded in consensual multimodal referents from shared experiences.

THE BALANCE CASE STUDY

The purpose of this study was to investigate how dance students learn about the physical concept of balance within the framework of dance. We were inspired by Laws' work with dancers (21) to teach students to distinguish between steady and unsteady balance positions. Towards this goal, students became acquainted with conditions for maintaining balance in relation to the constructs of 'area of support' and 'center of mass'.

The students learnt that 'Area of Support' is the space confined within the perimeter around all the body's contact points with the floor. For example, Fig. 3 illustrates the area of support for a standing position with both feet on the floor.

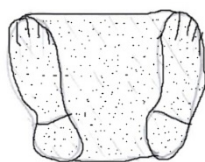


Fig. 3: The 'Area of Support' is the dotted area.

Regarding the 'center of mass', within the context of this case study it was impossible to provide a formal definition involving calculations. The students experienced an intuitive notion of the center of mass as the point in which the downward force of gravity appears

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

to act on the body as a whole. In the dance world, this point is referred to simply as *the center*.

As to the conditions of balance, a person is balanced if the center of mass lies directly above a point anywhere within the area of support. In the context of dancing, the students experienced two possibilities of balance: a steady balance in which applying a force on the person does not lead to a fall, and an unsteady balance in which applying even the slightest force could lead to a fall.

The learning process

In the present research, a group of twelve 10th grade high school female dance students participated in four consecutive lessons of 90 minutes each. The lessons were conducted in the school dance studio by the instructor using embodied pedagogy, which included a physical experience of each of the concepts prior to their academic learning in class. In the fourth and final lesson, the students were required to present a movement sequence including three balance positions and transitions between them.

The following is a short description of the lessons.

The first lesson began with improvisation of feeling balanced and unbalanced. The students realized the contribution of each of the touch points with the floor to their balance. Following the first experience, the instructor explained the meaning of ‘area of support’ and pairs of students marked their partner’s area of support for a given position that they formed as shown in Fig. 4. In addition, the students were instructed to slightly push their partners and check whether their partners lose balance. At the end of this activity the instructor named each position as steady- or unsteady-balanced positions.

Motor Skills, Creativity, and Cognition in Learning Physics Concepts



Fig. 4: Practice of marking the area of support, in the balance case study.

The second lesson began with Feldenkrais exercises (see Fig. 5) dealing with stability (20). Following the Feldenkrais exercises some students claimed that “*when the area of support is greater, the position is more stable and therefore, it is difficult to fall*”. The discussion at the end of the lesson involved also cultural and emotional aspects of stability, such as stability in life, financial stability, and stability in relationships.



Fig. 5: Feldenkrais exercises in the balance case study.

The third lesson began with improvisation. The instructor asked the students to walk around the room when the music was playing and feel the floor. She asked them to imagine that each part of their body, which she named, is like a motor that incites the rest of the body. Following this exercise, the instructor asked them to imagine the body as a small ball and to try and condense their body’s weight into the ball as if the ball were the motor that incites the movement. The rationale of this activity was to encourage the students to imagine the ball as a center of mass. At the end of the movement

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

improvisation the instructor asked students where they imagined the central ball to be in their body. Most students believed that their central abdominal area was that point, which is indeed the center of mass when standing up.

The students were surprised to realize that the center of mass is not always in their abdominal area (Fig. 6), as experienced previously and depends on their position.

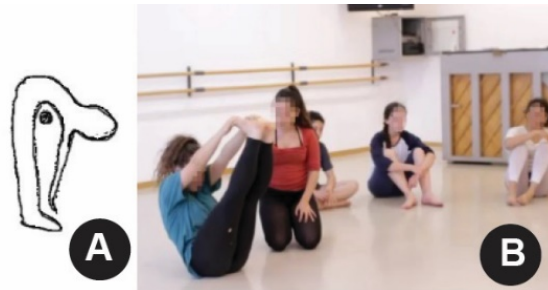


Fig. 6: A - The center of mass is external to the body, B - Practice of finding the center of mass.

For example, when raising their arms over their head, the center of mass is higher than the abdomen; when moving their arms to the right, the center of mass shifts to the right. The students' greatest surprise was that the center of mass could even be exterior to their body in certain positions such as when leaning forward as shown in Fig. 6. Interestingly, this fact is surprising even to professional dancers.

Following the three lessons, the instructor explained the conditions for maintaining body balance. First, she outlined with her finger a perpendicular from the center of mass to the area of support and showed that the smaller the support base, the more limited is the possibility of maintaining balance. This is the case, for example, when standing on tiptoes. Following some demonstrations with one of the students, the students practiced in pairs maintaining a stable structure with one, two, three or four contact points. One of the students in the pair had to mark the center of mass projected directly above the area of

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

support in the position performed by her partner as shown in Fig. 7. Afterwards, the instructor asked one pair to observe another pair of students, to examine the explanation provided by the performing pair and to conduct a discussion.



Fig. 7: A - Condition for balance: Practice of marking the area of support.
B - Condition for balance: Practice of finding the center of mass.

In **the fourth and final lesson**, the instructor asked the students to solve some movement problems related to the concept of balance. For example, the students were asked to stand with their legs adjacent to the wall and try to squat as shown in Fig. 8. The students realized it was not possible and provided an explanation.



Fig. 8: An example of a movement problem.

The balance summative project

At the end of the final lesson, the instructor asked the students to divide into groups and create a movement sequence of three balanced positions. After presenting the movement sequence, the students had to determine whether each position was steady or

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

unsteady balanced. The sequential movement task comprising the three balance positions demanded creativity and reflection. The positions chosen by each student were unique for each pair of students, who presented their movement sequence, including transitions from each position to the next. Fig. 9 depicts two pairs of students explaining one of the balance positions of the sequence they composed. In Fig. 9A a student explains how the position demonstrates a balance condition. She explained that the area of support is only the foot and showed how the imaginary perpendicular line projects directly from the center of mass point to the area of support. The students showed how swaying forward and backward would not affect the dancer's balance, since the center of mass is still directly above the foot's area of support. Although a movement forward or backward would not cause the dancer to lose balance, the students still defined the position as an unsteady-balance position due to its volatile nature.



Fig. 9: From the movement sequence: Two Pairs of students (A, B) show a position, judge it as steady balanced or unsteady balanced.

In Fig. 9B the students explained that although the area of support is relatively wide and includes both feet, the student turned her waist in such a position, which shifted the center of mass to the peripheral area of support in the outer edge of her left foot. Any slight movement of the dancer to the left would have thrown her off balance and therefore this position was categorized as unsteady balance position.







Motor Skills, Creativity, and Cognition in Learning Physics Concepts

Table 1 describes the movement sequence of a pair of students and their explanations. The pictures were extracted from the video of the students' presentation. The students chose to elaborate three balance positions (Fig. 10A, 10D, & 10F) which are marked in grey in the table. The students used physical terminology, motor skills, and gestures in their summative projects. They used the terms steady balance and unsteady balance correctly in their work and used body gestures to explain these terms, such as pointing to the center of mass point, to the area of support, and to the imaginary perpendicular line connecting them. An interesting finding was the students' differentiation of a *highly/totally unsteady balance position* as shown in Fig. 10F and *relative unsteady balance positions*, which were less unsteady as shown in Fig. 10A and Fig. 10C.

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

TABLE 1

Frames from a movement sequence of a pair of students (Fig. 10A-10F) and their explanations.

Frame	Judgment	Explanation of the student
	Unsteady balance	Despite the wide area of support, which includes both hands and a foot, the center of mass is situated in the outer rim of the area of support and a slight movement would result in the dancer's loss of balance. Although the position is relatively stable, any movement toward her arms would still maintain the center of mass above the area of support, however, any movement to other directions would result in a loss of balance.
	Unsteady balance	Transitional position. This position was not part of the three dance sequence positions required in the project but was a transitional position mandatory when shifting to the next position as shown in Fig. 10D. The dancer lost balance when setting her leg down while shifting to the next position.
	Unsteady balance	Transitional position when shifting to the next position as shown in Fig. 10D.
	Steady balance	The area of support surrounds both feet when standing in a straddle stance, and the center of mass still remains above the rim of the area of support even in case of slight movements. It is only if the dancer is pushed vigorously forward that she may lose her balance.
	Highly unsteady balance	The center of mass is at the very rim of the area of support.
	Highly unsteady balance	In order to remain in this position, she is required to move her arms from behind her back to the front, thus shifted slightly the center of mass. This action assisted in maintaining the center of mass above the area of support.

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

THE ANGULAR VELOCITY CASE STUDY

The pedagogical goal in this case study was to teach physics students the difference between linear velocity and angular velocity. Angular velocity was taught within the topic of circular motion. Attached is an example depicting the difference between the two concepts.

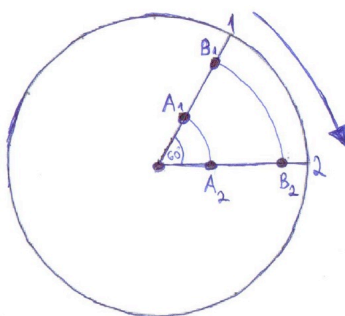


Fig. 11: A model manifesting the difference between linear velocity and angular velocity.

In Fig. 11, Points A & B are advancing along a circular path in a clockwise direction from time Point 1 to time Point 2. Point A is advancing from A₁ to A₂, and Point B from B₁ to B₂. Point B must travel a greater distance (the length of the long arch in Fig. 11) compared to the distance that point A travel (the length of the short arch in Fig. 11) during the same time. The distance that the two points must travel per time is called linear velocity. Linear velocity is defined as the linear displacement over time. The linear velocity of Point B is greater than the linear velocity of Point A.

Angular velocity is defined as the angular displacement over time of a body in a circular path. The angular velocity of Points A and B moving from their respective Point 1 to Point 2 are the same, because the segments connecting each of the points to the center of the circle advance at the same time in the same angle (in Fig. 11, the angle is 60°).

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

The learning process

The concept of linear velocity was studied during a regular physics class in a standard classroom setting. The concept of angular velocity was taught as part of embodied-pedagogy classes in a dance studio by the instructor of this research. These students were all female art students in various disciplines (art, video art, music, or dance). The research study lasted four months. During this period, each student met with the instructor for a total of seven hours. Some of these meetings were done in groups and some individually. At the end of the process, the students were required to submit a final project in groups, each in her own creative modality, on the topic of angular velocity. They had a month to prepare the final project, which will be described and analyzed in depth. The following is a short description of the learning process.

Working in a dance studio, the learning process begins with improvisation in circular movements on different body parts, where the instructions were: “*Move your hands in circular way, move your head in circular way; your feet; your hip,*” and so on. Students may move their limbs as they wish, such as varying movement size and rate. After the improvisation, the students were asked to stand alongside each other in row formation, and a bottle was positioned to the left of the left-most person (see Fig. 12).



Fig. 12: Enacting angular velocity by walking around a fixed-point in the collective circular activity.

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

The students were asked to walk around the bottle, keeping the row intact, which the students interpreted as a straight line. After some trial and error, the students negotiated a collective method to circle the bottle together, with those farther away from the bottle walking faster.

During a discussion of the collective circular activity, described above, the instructor lodged her elbow in the floor as a pivot and rotated her forearm. Specifically, the instructor marked the collective motion of individual dancers along a shared radius as shown in Fig. 12. She thus juxtaposed the students' common angular velocity vs. their unique linear velocities. The instructor, herself a dancer, thus used 'marking' (a miniaturized version of the full-body movement) as shown in Fig. 13. Marking, typically serves dancers "*as an anchor and vehicle for thought*", p. 2864 (22), for individual and collective reflection, instruction, and planning of action.



Fig. 13: The use of marking referring to the collective circular activity by the instructor.

Next, the instructor and students sat on the floor to reflect on the activity. Finally, the instructor asked the students to use paper and pencil to create a representation of the movement in the collective circular activity.

One month after the lessons, the students participated in 20-50 min. clinical interview, which included: (a) a request to draw the collective circular activity and explain the drawings; and (b) a paper-and-pencil physics question, which the students were asked to answer orally. The question concerned the difference between linear and angular

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

velocity. Of the 11 students, 9 succeeded in answering the paper-and-pencil question during the clinical interviews. Of these 9 students, 5 gestured with their forearm, similar to the instructor's marking during the intervention (see Fig. 14).

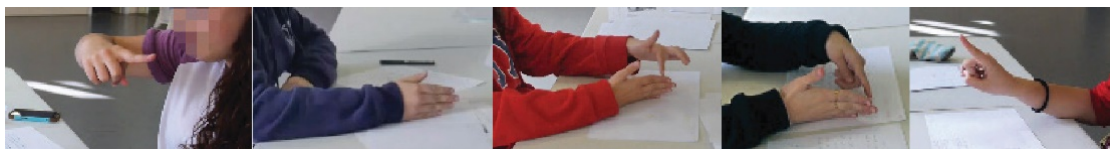


Fig. 14: The use gestures analogous to the instructor's marking.

An extended description of the role of the marking in the angular velocity case study in the context of the embodied pedagogy is described elsewhere (23).

One month after the interviews, the students participated in a concluding lesson, and then each student was asked to explain the concept of angular velocity to three science students from a lower grade, in any way they chose. Of the 8 students who were asked to explain the angular velocity concept to younger students, 7 chose to ask them to stand up and experience the concept of angular velocity in a manner similar to the collective circular activity. All the learning process was videotaped as preparation for micro-ethnographic analyses of the multimodal interactions (24).

The angular velocity summative project

At the end of the entire learning process the instructor asked the students to prepare summative projects: *“Prepare with one or two partners a creative project associated with the concept of angular velocity”*. The students had a month to work on the project and were told that they would discuss their project with the class.

We now describe four summative projects. We will provide a detailed description of a video art project of two students.

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

Project 1: Two physics students, one of them an Art major and one a Film major, prepared a video clip for the project. Fig. 15 presents some frames from the video clip. The video clip can be accessed at goo.gl/rFVEmk. The students chose the video clip of “Total Eclipse of the Heart” by Bonnie Tyler. When the words “turn around” in the chorus are played, one of the student trickles drops of paint from a bottle to a paper surface and paints with her finger circles on the paper.

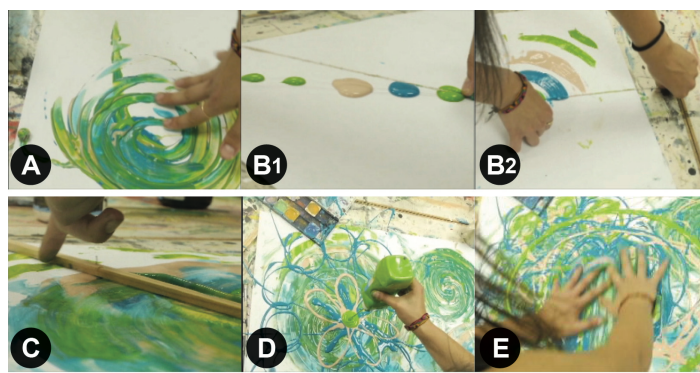


Fig. 15: Frames extracted from the original video created by two students. They used water colors, paper, a thread, a stick, their hands, and music lyrics suited for the topic of circular motion.

The music then shifts to the Beach Boys song, “I Get Around”, and while the music is played the student sprinkles circles on another paper from paint bottles at fixed distances from each other. She then takes a thread (as seen in Fig. 15B1) and moves it in circular motion, as seen in Fig. 15B2. She then repeats the action with a stick in place of the thread (Fig. 15C). The student pours water colors and draws flowers (Fig. 15D), and finally she mixes the colors using her hands on the paper in circular motions, as seen in Fig. 15E.

The activity done by the students with paint, thread and stick was analogous to the collective circular activity in the dance studio, in which the colors correspond to the students in each circle marked by a different color. Like the collective circular activity,

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

each color used in the project marked a different circle and a different linear velocity. The thread and stick enabled demonstration of the angular velocity, which remains the same for all the differently colored circles. Unlike the elbow-pivot marking, in which the forearm stands in for an undifferentiated student collective, the hand's motion also enables to articulate individual students with individual fingers, thus accentuating the conceptual tension between linear and angular velocity.

When presenting the video clip, the students explained that they used the same amount of colors for all circles. They claimed that *“the color of the outer circle, which is set farthest from rotation axis to which the thread and stick were affixed (by the student) is used up faster, since it is the largest circle and therefore creates the greatest arch.”* They further explained that *“the color which is farthest from the rotation axis has a greater linear velocity compared to the other colors which are closer to the circle's rotation axis. In fact, all colors as well as the paint drops on the thread or on the stick have the same angular velocity.”* The activity and the students' oral explanation correspond to the difference between linear and angular velocity as seen in Fig. 11.

The students clearly incorporated their personal viewpoint and interests in their project. The art students chose to use paint, whereas the video and photography student in the group chose to use her art skill in filming and editing to document the work. The students had the freedom to choose how to present their project and they chose paint, thread, stick, and music. All students reported that they enjoyed working on the project.

Project 2: Two physics students, one a Music major and one a Dance major, presented for their final project a dance they named “The Circle of Life”. Selected photographs from the dance are presented in Fig. 16. The dance was choreographed to the song

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

“Circles” by the Israeli composer and singer Idan Raichel. The girls first presented the dance, followed by an explanation. The students explained that the opening position (Fig 16A) portrays an embryo and the final laying position portrays death (Fig. 16G). Following the first position, the girls crawled and walked on a circle drawn on the studio floor (Fig. 16B) then they stood up and began running (Fig. 16D). At first, each student ran separately and later they embraced (Fig. 16E) and ran while holding hands (Fig. 16F). The students explained that running separately represents the period when each person is single before finding a spouse with whom they continue their life. The coupled run was along two concentric circles representing the individuality of each person within the couple, whereas holding hands represented their unity. The girl dancing in the outer circle explained that she has to run faster and in larger steps in order to keep up with her partner and claimed that “*This represents the co-existence of living with your spouse*”.

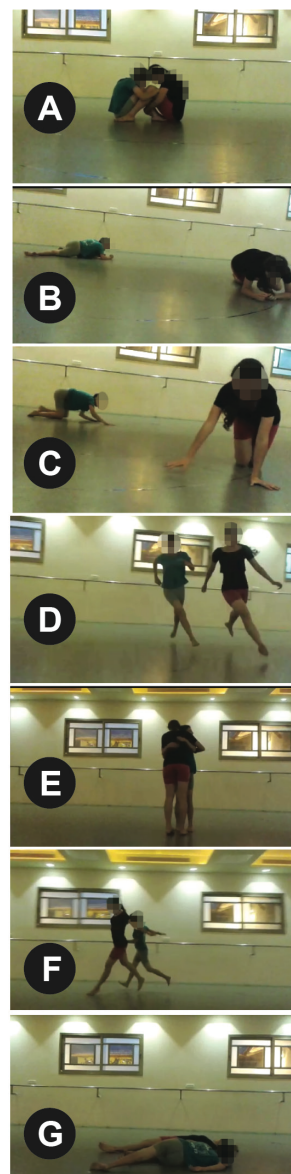


Fig. 16: Frames extracted from the “circle of life” dance created by two students. They moved on a circle drawn on the studio floor with background music related to circles.

At the end of the dance the circles are cut short and the students lay on the floor in the final position symbolizing death.

In this project, we see the students’ explicit understanding of the concepts of angular velocity in the coupled run with their hands spread out. In this run, the students claimed

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

that “*each one has their own linear velocity and together they share the same angular velocity*”.

In addition to the understanding of the two concepts the students linked the concepts to real life by analogizing angular velocity to real life as a couple, and linear velocity to life as an individual within a couple. The girls linked the physical concepts regarding circular motion to the notion of the circle of life from birth until death through family life. The dance position chosen for the dance, the music accompanying the dance, and the story revolving around the dance are tightly linked to the embodied pedagogy and the taught concepts. One can recognize in the dance, the influence of the collective circular activity in which these students had participated during the embodied pedagogy lessons.

The students ran side by side similar to the circular walk done in the collective circular activity. The students exhibited creativity and a profound understanding of the concepts taught and linked it to their personal world and interest.

Projects 2 & 3: Fig. 17 depicts artifacts from two more physics projects presented by an Art major and Music major. Unlike the other projects, these students chose to present a model.

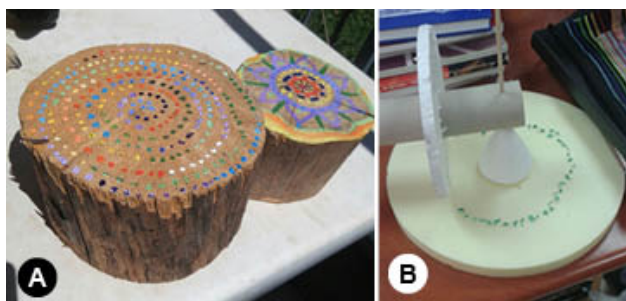


Fig. 17: A - A painted log by two students, B - An olive harvest by two students

The students who made a painted log as shown in Fig. 17A, explained: “*We selected a log because one can see the age of the tree. You can only see it after the tree is cut and its*

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

life ended. The circles created while the tree grows tell us its life story. We decided to add color which adds beauty to the tree life story and this is the way we chose to “thank” the tree for its contribution to humanity. On the small tree trunk we painted a color mandala created by several circles, while on the larger trunk we created a spiral made of numerous colorful small dots, which represent the growth of the tree”. The students who made the olive harvest as shown in Fig. 17B, explained: “We imagine people around the paper roll who squeeze the olives”.

All the summative projects manifest a clear learning process by the students. The students drew from the physical concepts as well as from cultural and emotional perspectives. All students created interesting projects that incorporated their personal skills, interests, and abstract understanding of life, while linking them to the conceptual knowledge targeted by the science curriculum. We argue that our narratives document individual contributions to, and evolutions through, a classroom sociogenesis of new semiotic bundles, where conceptual meanings are collectively grounded in consensual multimodal referents from shared experiences. We believe the embodied pedagogy enabled the composition of these highly complex projects presented by the students.

CONCLUSION AND DISCUSSION

What are best practices for leveraging full-body activity as a means of supporting physics learning? The case studies presented in this article illustrate how this can be achieved through the interplay between the student’s naïve sensorimotor knowledge and disciplinary knowledge promoted by an embodied pedagogy. This constructivist pedagogy involves physical–dynamical engagements: directed bodily experiences (‘informed movements’); improvisation in movement mediating between imaginative and

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

reasoning, body actions, and feelings; techniques combining walking and talking; selected aspects of the Feldenkrais method; and relaxation. The movement activities were carried out in a dance studio, which acted as a hybrid learning environment enabling students to connect their artistic interests and talents to school learning. The realization of these connections is a desirable feature of hybrid environments. In the present study, the embodied pedagogy was fitted to a dance studio, but it can be appropriate to sport halls or even an empty classroom.

The case studies analyzed and interpreted summative projects that students carried out after completing the learning modules. Students' summative projects were delivered in a variety of modalities, such as video art, music, and dance, and included inscriptions and enactment of selected elements from the movement activities. For example, the final projects in the angular velocity case study were influenced directly from the collective circular activity enacted in the embodied-pedagogy lesson, which they had experienced.

In both case studies the students exhibited creativity and a profound understanding of the abstract concepts taught. They linked the ideas to concrete representations, to their personal world and to their private interests. The complexity of the balance and angular-velocity concepts is apparent from the learning process described in the case studies. The depth and insight of physics understanding that the students manifested in the summative projects are much beyond what can be achieved in regular instruction. Some of the notions that the students discovered are surprising even to experts. In addition, the students also demonstrated affective life-philosophy relations with the subject matter (e.g., cycle of life and death).

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

Corroborating principles of embodied design, this study has supported the plausibility of STEM (science, technology, engineering, and mathematics) curricula in which: (a) abstract concepts are designed as grounded in sensorimotor problem solving; and (b) multimodal reflective expression plays a key role in raising experiences to collective consciousness and couching insights in disciplinary forms.

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Motor Skills, Creativity, and Cognition in Learning Physics Concepts

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Motor Skills, Creativity, and Cognition in Learning Physics Concepts

Legends

- Fig. 1:** An example of improvisation in movement, a component of the embodied pedagogy.
- Fig. 2:** An example of relaxation, a component of the embodied pedagogy.
- Fig. 3:** The ‘Area of Support’ is the dotted area.
- Fig. 4:** Practice of marking the area of support, in the balance case study.
- Fig. 5:** Feldenkrais exercises in the balance case study.
- Fig. 6:** A- The center of mass is external to the body, B - Practice of finding the center of mass.
- Fig. 7:** A - Condition for balance: Practice of marking the area of support.
B - Condition for balance: Practice of finding the center of mass.
- Fig. 8:** An example of a movement problem.
- Fig. 9:** From the movement sequence: Two Pairs of students (A, B) show a position, judge it as steady balanced or unsteady balanced.
- Fig. 10 (inside Table 1)
- Frames from a movement sequence of a pair of students (**Fig. 10A-10F**) and their explanations.
- Fig. 11:** A model manifesting the difference between linear velocity and angular velocity.
- Fig. 12:** Enacting angular velocity by walking around a fixed-point in the collective circular activity.
- Fig. 13:** The use of marking referring to the collective circular activity by the instructor.
- Fig. 14:** The use of gestures analogous to the instructor’s marking.
- Fig. 15:** Frames extracted from the original video created by two students.
They used water colors, paper, a thread, a stick, their hands, and music lyrics suited for the topic of circular motion.
- Fig. 16:** Frames extracted from the “circle of life” dance created by two students. They moved on a circle drawn on the studio floor with

Motor Skills, Creativity, and Cognition in Learning Physics Concepts

background music related to circles.

Fig. 17: A - A painted log by two students, B - An olive harvest by two students.