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Embodied cognition and teaching STEM: Tenets to explain and enhance a middle school science project

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Embodied Cognition and Teaching STEM:
Theoretical Tenets in Action on a Middle School Science Project

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Abstract

STEM pedagogy is a popular area for research and discussion. The empirical literature on this topic supports a variety of approaches (e.g., inquiry-based) to help instructors spark student interest create an effective learning environment, and foster long-term retention and transfer of information related to STEM topics. One potential approach is to use tenets of embodied cognition, in which behavior and cognition emerge out of real-time sensorimotor behavior of the individual situated within a particular context, to implement strategies to enhance STEM pedagogy. We applied the six lessons of embodied cognition to understand the beneficial aspects of a middle-school project on water quality and concluded with recommendations of incorporation of the six lessons for STEM pedagogy at large.

Keywords: *STEM, embodied cognition, middle level education, STEM pedagogy*

In contemporary society there is a need for individuals to understand STEM and enter the STEM workforce, in which there are millions of unfilled jobs (Margot & Kettler, 2019; Smithsonian Science Education Center, 2023). Unfortunately, the unmet need for an increased STEM-literate workforce has been met with a declining interest in STEM as students move through their early education, which could be due to a plethora of factors including, but not limited to, students' STEM career knowledge and understanding of activities associated with such careers, STEM and mathematics self-efficacy, instructor perceptions of STEM, and pedagogical strategies implemented by instructors (Blotnicky et al., 2018; Margot & Kettler, 2019; Murphy & Beggs, 2005; Tai et al., 2006). To this latter point, Shahali et al. (2019) found that middle school students' interest in STEM topics may potentially decline as a function of the quality of teaching and the learning environment they reported experiencing, which indicates that middle grades are a particularly important time to introduce unique and evidence-based approaches to engage these students.

From a pedagogical standpoint, the way in which instructors structure and deliver their lessons provides a window into how they themselves believe students think and learn (Mayer, 2005). As long ago as the 1960s, middle grades were seen as a weak link in science education (Gatta, 1970), which led to the formation of the Intermediate Science Curriculum Study (ISCS), a movement that encouraged the use of activity-centered learning and process skill development. The ISCS movement emerged to combat the engrained and static middle grades science pedagogical approach, which Carleton (1967) noted as, "...total emphasis on description, utilitarian uses, technology, and memorization, with little or no laboratory work for the pupils…" (p. 25). In the mid-1990s, the American Association for the Advancement of Science (AAAS) and the National Research Council (NRC) also began advocating for a shift from science instruction focused on fact-based memorization (e.g., the traditional approach) to more hands-on and inquiry-based models. Such a proposal was to challenge instructors to get students to be more active in their learning of the material rather than envision them as largely passive receptacles of information disseminated unilaterally from the instructor and/or textbook (Gibson & Chase, 2002). In fact, and for quite some time, such an approach has been encouraged across many educational environments and empirically linked to student success, especially in terms of applying what they learned in the classroom to everyday life (Dewey, 1916; Doyle, 2012). Using the traditional teacher-dictated approach to instruction has repeatedly been linked not only to deficiencies in students' knowledge acquisition and maintenance, but also in their abilities to translate what they learned in the classroom into real-world action situated across varied sociocultural contexts (Khalaf & Zin, 2018; Kiraly, 2017; Olk, 2003). In a contemporary STEM needs sense, training individuals in such a way as to facilitate transfer of knowledge into STEM careers is of utmost importance.

Inquiry-based approaches, in which students are challenged to construct knowledge via activity (e.g., problem-solving, engaging in scientific processes, practice, innovation, collaboration, and communication) was shown to be promising through empirical work (Gibson & Chase, 2002; Zakeri et al., 2023). Khalaf and Zin (2018) noted this pedagogical approach to be rooted in Piaget's (1952) cognitive developmental theory, however it was every bit as consistent with the perspective of Vygotsky (1978). Both Piaget and Vygotsky proposed a constructivist approach to the development of knowledge in which individuals' activity in the world, and especially within a sociocultural world for Vygotsky, was a key driver of knowledge attainment. Such approaches starkly differed from the traditional, more passive, pedagogical approach. Armed with the Piagetian and Vygotskyan theoretical perspectives, practical research into inquiry-based models of instruction blossomed. Specifically, Gibson and Chase (2002) found middle school students who engaged in science education via the traditional approach (e.g., memorization, teacher-led, etc.) showed lower achieved outcomes relative to an inquiry-based group. Beyond just academic outcomes, engagement in such activity- and inquiry-based activities can have significant and positive impacts on middle school students' perceived utility of STEM, as well as interest and intent to continue with STEM (Brown et al., 2016). Such outcomes have been demonstrated in many studies within the past 20 years and inquiry-based instruction remains one of the recommended strategies for STEM education (see Thibaut et al., 2018, Zakeri et al., 2023).

Despite the flourishing of strategies and increased positive outcomes for teaching STEM that emerged via the constructivist perspectives, recent empirical evidence within the cognitive development literature challenged some of the basic tenets of these perspectives. Through this work, the theory of embodied cognition emerged and provided a more complete perspective of cognition, one that better accounted for real-time acquisition and demonstration of knowledge. The critique of the Piagetian and Vygotskyan perspectives related to the notion that as individuals interacted in their world to construct knowledge, this knowledge built up as an internal symbolic representation, or concept, and with enough experience this concept existed and operated independent of previous and immediate actions, consequently, ignoring the body as a key factor in real-time cognition (Savelsbergh, 2005; Thelen & Smith, 1994; 1998). This approach represented traditional cognitivist approaches in which these "concepts" have been the explanatory mechanism for the apparent stability of human cognition (Keil, 1994). However, developmental work has demonstrated that behavior and cognition are not as stable as such traditional approaches purported. Rather, behavior and cognition have been shown to emerge via a confluence of continuously interacting factors, grounded in the real-time sensorimotor behavior of the individual situated within a particular context (Shapiro, 2007, 2011, 2012; Smith, 2005; Smith & Samuelson, 1996; Spencer et al., 2006; Thelen, 2000; Thelen & Smith, 1998). In other words, the actions in which individuals engaged within particular contexts contributed to how they perceived, thought, learned, remembered, and applied information. Therefore, the tight coupling of cognition to the world in which individuals behaved served to adapt thought processes to the immediate real-world context.

An understanding of the basics of the more dynamic approach of embodied cognition may help STEM instructors to design lessons and activities that better align with the understanding of how individuals learn, apply, and retain information. Such an understanding of this approach would seem of tantamount importance at the middle school level given that Shahali et al. (2019) speculated that teaching and learning quality may be significant contributors to middle schoolers' declining interest in STEM. Embodied cognition-informed instruction could ensure that instructional activities are structured to align with middle schoolers' cognitive wheelhouse so as to facilitate understanding of STEM information, and possibly enhance interest and intent to persist in STEM, as well as knowledge and experiences of the utility of STEM. Smith and Gasser (2005), drawing from developmental research, outlined six lessons to foster the development of embodied cognition, which we believe to be a nice roadmap that could be used by middle school STEM instructors to enhance their instruction. The six lessons proposed were: a) Be multimodal, b) Be incremental, c) Be physical, d) Explore, e) Be social, and f) Learn a language.

The Six Lessons of Embodiment

The first lesson, *be multimodal*, operates on our understanding of sensory systems and the dense interconnectivity across them within the nervous system. As individuals interact in the world, they make contact with it across multiple sensory systems, which as Edelman (1987) and Sporns and Edelman (1993) pointed out, creates a degenerative neural system through which individuals can still function even if one of the sensory components is absent. This degeneracy allows for intersensory tutoring such that when individuals encounter aspects of the world concurrently across multiple sensory modalities, the activities of neurons within each sensory modality become mapped together given the correlated nature of activity across the sensory systems. Further, as individuals act in the world and experience different aspects of it across single and multiple sensory modalities in real-time, the updating of the mapping across the sensory systems is a continuous process and is intricately related to the actions within the world. In application, STEM instructors could ensure instructional design that permits students to experience information across multiple sensory modalities, which may permit stronger and more varied connectivity and mappings across the multiple sensory systems.

The second lesson, *be incremental*, operates on the understanding that as individuals develop new knowledge and skills, new experiential and multimodal opportunities emerge. Specifically, the emergence of novel behaviors opens the door for novel ways of acting in the world, and thus novel multimodal mappings and higher order understandings of the world. In this context, the structuring of instruction should be done in such a way as to capitalize on this notion. For instance, STEM instructors, rather than providing students with a full task to complete all at once, could set the stage for students to learn content and skills incrementally such that when new knowledge and skills emerge, they have the opportunity to update and modify their multimodal mappings.

The third lesson, *be physical*, operates on the idea that as individuals experience the complex world and work to make connections and detect regularities, sometimes cognition and knowledge emerge between the body and environment. In other words, when in a physical environment, individuals are able to distinguish between aspects of the world based on location and space, not necessarily the aspects directly. For instance, young children can associate a name of something, even when it is out of sight, simply via observation of directional cues from an adult and location placement (Baldwin, 1993). In the context of STEM pedagogical strategies, instructors situating activities in the physical world, and providing opportunities for students to actively engage (looking, acting, etc.) within that world, especially in the context of learning new information, will permit students to use their bodily experiences to establish continuity in their cognition and knowledge of the physical world.

The fourth lesson, *explore*, emphasizes that individuals may enter a learning situation without specifications for what is to be learned, nor how to learn it, but still manage to discover solutions to these through multimodal activity within the situation. Empirical evidence with infants through adults demonstrates that discovery and learning occur across a variety of tasks, ranging from basic perceptual-motor tasks, higher-order cognitive tasks, and learning STEM-related topics and skills, all without explicit instructions on how to do so (Asghar et al., 2012; Bevan et al., 2015; Bojczyk & Corbetta, 2002; Williams et al., 2015; Yue, 2022). An important aspect to understanding the integral part of exploration to the multimodal learning process relates to the fact that when presented with the learning situation, each individual meets it with rich developmental histories, levels of knowledge and experience, preferences, interaction styles, and in short, different multimodal mappings from which they approach the problem solving. This indicates that exploration is essential for each individual to discover solutions through the real-time and continuous reorganization of their multimodal mappings to meet task demands. Therefore, although individuals may arrive at a similar end within the learning process, the trajectory toward discovery of the solution is likely quite unique. STEM instructors with an understanding of the *explore* aspect of embodiment may present students with the task to be completed without any, or very little, prescription for how to solve the task.

The fifth lesson, *be social*, emphasizes the importance of embedding the learning and behavior of individuals within a social context, in which interaction with other learners is integral to the learning process. This, as mentioned earlier, fits with the sociocultural constructivism of Vygotsky, in that through social interactions individuals develop new strategies for solving problems and explaining information, as well as new content knowledge and ways to collaborate and understand varied perspectives (Vygotsky, 1978). In the context of embodiment, social interaction allows for a rich multimodal learning opportunity in which participants learn that their thoughts, actions, and reactions become correlated to the thoughts, actions, and reactions of other participants, through which knowledge and skill learning is scaffolded to higher levels of shared understanding. Through multimodal scaffolding opportunities, especially when the interaction includes more mature (in knowledge and skill) individuals, knowledge and skill development increases concurrently across those involved in the interaction, consequently opening the door further to a wider variety of multimodal opportunities for interaction, exploration, development, and application. In STEM, one could make the

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argument that social interaction is one of the key drivers for the utility of STEM learning communities (Carrino & Gerace, 2016) as well as citizen and community science approaches (Nation & Hansen, 2021; Parrish et al., 2018). Ultimately, with a knowledge of the positive ramifications of social interaction, STEM instructors should take advantage of the rich multimodal opportunities afforded by such interactions.

The sixth lesson, *learn a language*, emphasizes that language learning has its roots within basic sensory, perceptual, motor, and social processes. In addition, once it emerges, it is a powerful tool that provides continuity to the ongoing and previous lessons of embodiment and thus fosters shared understanding, increased learning opportunities, and enhanced complex reasoning. Instructors likely understand that as students enter a STEM lesson, there is quite a lot of vocabulary to be learned. Consequently, emerging from the basic vocabulary, students develop a language in which the instructor and peers can interact and communicate, working toward a shared understanding of concepts and procedures. Importantly, STEM instructors may be able to foster continuity in the language and shared understanding, as well as the opportunity for more sophisticated understandings, problem-solving, and application, through the structuring of the learning environment according to the aforementioned lessons of embodiment.

In the remainder of this paper, we attempted to apply the six lessons of embodiment (Smith & Gasser, 2005) to understand why a local middle school student-favorite STEM activity has been so well-received and successful. First, we connected with a local, award-winning middle school STEM instructor and gathered details about how he implemented his lesson on understanding concepts, measurement, and impact of water quality. Second, we deconstructed each key step in his lesson and highlighted how each step aligned with specific tenets drawn from the lessons of embodiment, and consequently supported the multimodal learning process. Further, in keeping with the truly dynamic fashion of the learning process, we highlighted how each tenet of embodiment was concurrently nested within each step. Then, we ended with practical considerations for how STEM instructors can use the tenets of embodied cognition to design effective lessons, enhance students' understanding of essential STEM concepts and procedures, and consequently foster effective and efficient transfer of the knowledge and skills developed to real-world STEM careers.

Water Quality Monitoring Activity and Embodiment Tenet Mapping

In-Class Lesson and Presentation Creation

Step Description

The first step of the process was to make sure students had an underlying understanding of water quality itself. The curriculum was based on the Georgia "Adopt a Stream Format" and included the students working through an in-class lesson during which they created a presentation about water quality, how water quality was measured, what a watershed was, what dissolved oxygen was (and how it was affected by different factors), what pH was and how different bodies of water should have different pH levels (for instance, that ponds should be approximately 7, brackish waters should be approximately 8, and swamps should be approximately 6 because of different biological factors), and what factors affect salinity, clarity, nitrate, and phosphate levels. This presentation was followed by an assessment to make sure students had a baseline level of understanding before proceeding. This step was designed to help students become familiar with how the presentation and in-class lessons worked to assist their multimodal learning.

Embodiment Mapping

Students began to develop their understanding of water quality through in-class lessons delivered by their instructor via audiovisual media, and thus the basic content information was experienced multimodally and temporally correlated. This basic content served as the initial base from which knowledge later developed, grew, and was continuously integrated with, and connected to other knowledge incrementally. In an incremental fashion, the instructor challenged students to experience the physical context through the opportunity to explore scholarly visual media (e.g., photos, maps, etc.) of the watershed and surrounding landscape available on the internet. Through this exploration, albeit in a two-dimensional space, students perceived and acted upon the information discovered to develop a more sophisticated understanding and organization of this particular aspect of the physical world. All aspects of this initial portion of the larger project were nested within a social world, whether it be within the classroom setting, with partners, or via technology-enhanced communication with classmates. Further, all the information related to the project, including terms, names of procedures, tools, organisms, and geographic locations, among other things, were novel to the students and thus, through multimodal and social exploration, the students learned how to think about and communicate this new information in meaningful ways.

Equipment Training

Step Description

The next step of the project involved training the students to use the equipment necessary to measure water quality. This started with an in-class lesson about the specific sensors, how they are used, and how to keep them safe. After the lesson, students entered the wetland where they completed an additional lesson on how to use the equipment and store it safely. This lesson included the instructor modeling how to use the sensors, then, the students used the sensors to collect and analyze data. This allowed the students to demonstrate an understanding of when the sensors worked correctly and when they did not.

Embodiment Mapping

Learning how to use the equipment, modeling how to use the sensors, letting the students collect data, and helping the students analyze data required multimodal engagement. Students had to listen, watch, touch, and explain their results. This part of the activity was incremental because students engaged in these steps sequentially in order to successfully complete the activity. In addition, it was also incremental in the sense that students used prior knowledge in order to effectively understand and interpret information gathered from the equipment. These steps occurred in the physical environment as students actively learned to use the equipment to explore real world characteristics of the wetland, such as measuring and interpreting the pH of the water. They navigated their environment using specific equipment to gather data, then subsequently analyzed and interpreted it. This activity unfolded within a social context, in which students interacted with the instructor and peers through the novel communicative system they had developed in the preceding steps of the project. For instance, students communicated with each other when help was needed, when results were explained and/or interpreted, and when they developed a shared understanding of the significance and application of the findings. The emergence of knowledge through this activity allowed for information to be transferred to novel contexts. While the concept of language in this context may be rudimentary, the knowledge and experiences it allowed the students to share was critical for the learning process.

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Trapping and Dipping Surveys

Step Description

The third step of the Water Quality Monitoring activity involved conducting dipping and trapping surveys, differentiating biotic and abiotic units in different wetland habitats, and learning to identify the six different parameters of water quality. These were all done by the students with the help of minor instructional cues written on presentation slides and verbally distributed by the teacher. The students specifically, when conducting trapping and dipping surveys and moving from abiotic to biotic, were investigating the differentiation between abiotic and biotic components of the different wetland habitats.

Embodiment Mapping

Measuring water quality and learning to differentiate the biotic and abiotic components of the wetland as they were situated in that context, was the ideal opportunity for multimodal learning. As students dipped water to be tested with the water testing equipment while they concurrently trapped organisms, they engaged multiple sensory modalities, through which previously learned information became integrated with novel information. In addition to being multimodal, it was also incremental in the sense that students took the water quality content learned in step one and procedural knowledge learned in step two to the wetland and integrated it with the identification and differentiation of biotic and abiotic. Immersing themselves in the environment supported knowledge acquisition through repeated cycles of perception and action in a “real” world context. Through immersion in these activities, students explored the wetland and learned the novel content via trial-and-error processes, rather than full prescriptive instructions, which fostered the discovery of varied ways to learn and solve assigned tasks. All of this occurred within a social context, in which students discovered task solutions collaboratively, using scientific language learned in prior lessons and also language that emerged as a function of exploring the new environment.

Identification and Handling of Organisms

Step Description

The next step of the project in which the students engaged involved identifying organisms after they had been trapped. This included handling all of the organisms that they caught, then using books to help with identification and differentiation of the organisms.

Embodiment Mapping

This step of the project was, by its very nature, multimodal, as students experienced the environments and organisms through vision, touch, smell, and (at times) sound. As an example, trapping and identifying marsh and swamp organisms in their respective habitats allowed for multimodal differentiation of the concurrently experienced sights, smells, sounds, etc., of the habitats in which the organisms were trapped. Additionally, this step was incremental in that all of the previous steps of the project were needed in order to know how to effectively trap, measure, identify, and integrate information. The students engaged directly with the physical environment, and detected regularities in the environment such as how they were more likely to see particular organisms in particular environments. For example, if the trapping occurred in the swamp, it was a partial biodiversity survey because it did not include plants, but if it was done in the marsh it was a comprehensive biodiversity survey because it did include plants. It was essential that the students worked together, using books and scholarly internet sites, to determine the organisms trapped and communicate this information amongst the group, during which time the students formed social relationships with each other and their instructor. And finally, almost all the communication between students and with the instructor was using spoken language and included the use of the new vocabulary that emerged as a result of the previous steps of this project.

Project Culmination

Step Description

The final step in this project was the culmination of all of the other steps. A main goal of this step was to tie the information from the time in the field back to information studied in class. Students reflected upon how the test on water quality happened before they used the equipment, how understanding the abiotic versus biotic contributed to the ecosystem, and how changes in one part of the system may have cascadic effects on the entire ecosystem.

Embodiment Mapping

After engaging in the preceding four steps of the project, students had the opportunity to re-engage with, and reactivate, the multimodal mappings and knowledge developed. This re-engagement and reactivation occurred within the context of applied and real-world scenarios which the student had yet to experience directly. For instance, if students were presented with a situation in which they discovered a bluegill fish in an area where only amphibians typically lived and bred, they were challenged to draw upon their knowledge and experience to identify this as an aberrant aspect of an ecosystem. Further, recognition of such an aberrant situation may have led to students drafting proposals for environmental stakeholders to take notice, understand the repercussions, and act. Through these situational challenges, students translated information, especially via the use of project-specific language, that they constructed multimodally and incrementally through active exploration in a social context and applied it to enact socially significant change within their own community.

Practical Implications

Given the structural changes that occur when STEM classes move to an inquiry-based approach, this is an ideal time for teachers to incorporate an embodied cognition approach as they create their lesson plans. While there are many ways to accomplish this, following the six lessons proposed by Smith and Gasser (2005) may be helpful.

First, remember that students experience the world in a multimodal fashion. How many modalities is each lesson stimulating? Is it possible to "add" a modality to the lesson? It may also be helpful to point out to the students when things can be experienced through multiple modalities (for example, how the sight of something relates to the feel or smell of it). Second, be mindful that learning happens incrementally. Skills emerge one at a time rather than all at once. Thus, students will do better when given tasks with concrete "one at a time" outcomes that allow them to update their knowledge base and integrate with previous knowledge. It is even better if they have time to practice their new knowledge before moving on to the next step. Third, be cognizant of the physical nature of learning. If possible, provide opportunities for students to have "hands on" engagement in a setting appropriate to the discipline. Because the brain has memories that exist separately for information that the student has learned as well as memories for physical actions, performing these together will enhance and strengthen both types of memories and provide further memory consolidation. Fourth, unleash the tool of exploration to your students. By emphasizing exploration, instructors create an environment that allows students to actively explore and find answers in real time. Additionally, when students are presented with a task without strict guidelines on how to solve it, they are free to explore different approaches and strategies. This exploration allows them to integrate sensory information, motor actions, and perceptual feedback. Fifth, don't forget about the social aspects of learning. When more experienced students engage in multimodal scaffolding, they can provide targeted support and guidance to less experienced learners. They can also employ a variety of modalities, such as verbal explanations, demonstrations, visual aids, or hands-on activities, to cater to different approaches and enhance understanding. Further, being social can involve collaboration and partnerships with community partners whenever possible, as these partners may initiate the process of inquiry as well as serve to guide less experienced learners. Finally, harness the power of language in your lessons. When students engage in STEM lessons, they are exposed to a significant amount of vocabulary, specific to the discipline, that allows them to speak a common language. This language builds a shared community, and a basis for interaction between students, peers, and instructors. In this sense, instructors need to structure their lessons so that the students understand and share vocabulary in their interactions.

Concluding Remarks

It is well established that society needs a sufficient number of STEM-trained students who are prepared for jobs in STEM-related fields. The push for STEM education is rooted in recognizing that these fields are crucial drivers of innovation, economic growth, and technological advancement. Furthermore, it is possible that STEM education can help address the skills gap, promote scientific literacy, and prepare students for careers in emerging fields. Moreover, STEM education could empower underrepresented groups, including women and minorities, by providing access to opportunities in high-demand fields.

By incorporating embodied cognition strategies, we saw how one middle school teacher encouraged his students' engagement in learning STEM concepts. The middle grades have been targeted as a critical time for attitudes towards science to develop, which presents an important opportunity for educators to apply principles of embodied cognition to enhance engagement during this period. Perhaps other teachers can incorporate similar techniques, and we can see middle school students' interest in STEM increase due to the quantitative and qualitative changes in teaching and the learning environment that accompany the use of an embodied cognition approach.

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