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Translating Embodied Cognition for Embodied Learning in the Classroom

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In this perspective piece, we briefly review embodied cognition and embodied learning. We then present a translational research model based on this research to inform teachers, educational psychologists, and practitioners on the benefits of embodied cognition and embodied learning for classroom applications. While many teachers already employ the body in teaching, especially in early schooling, many teachers' understandings of the science and benefits of sensorimotor engagement or embodied cognition across grades levels and the content areas is little understood. Here, we outline seven goals in our model and four major "action" steps. To address steps 1 and 2, we recap previously published reviews of the experimental evidence of embodied cognition (and embodied learning) research across multiple learning fields, with a focus on how both simple embodied learning activities—as well as those based on more sophisticated technologies of AR, VR, and mixed reality—are being vetted in the classroom. Step 3 of our model outlines how researchers, teachers, policy makers, and designers can work together to help translate this knowledge in support of these goals. In the final step (step 4), we extract generalized, practical embodied learning principles, which can be easily adopted by teachers in the classroom without extensive training. We end with a call for educators and policy makers to use these principles to identify learning objectives and outcomes, as well as track outcomes to assess whether program objectives and competency requirements are met.

Keywords: translational science, embodied cognition, teaching—learning, pedagogy, learning sciences

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MINDING THE (BRAIN) GAP

Currently, there is paradox in education: a focus on evidence-based research but an abandonment of the theories (Matsushita, 2017). For example, effective performance in clinical settings requires the integration between theory and practice. Yet there is a gap between theoretical knowledge as taught in the classroom and what K-12 students experience and learn (Hashemiparast et al., 2019). Furthermore, teachers' action-based classroom research, while often promoting student achievement, is often absent of robust links to theory and is liable to neglect the application of a deductive, empirical framework. One reason for this dearth of informed practice is a lack of a framework for translating theory to practice, and in this instance, linking embodied cognition and embodied learning to effective teaching.

To promote informed research-based decisions in education, the *No Child Left Behind* Act (2002) mandated "scientifically based" research, which was replaced by *Every Student Succeeds* Act (2015) calling for "evidence-based" interventions. Still, few educators are privy to the research advances in the science of learning (Weinstein et al., 2018). Further, the limited awareness of recent theoretical and empirical evidence in cognitive science constrains the dissemination and adoption of research findings. There is a need for collaborative models that emphasize a bidirectional flow from researchers to practitioners (Nutley et al., 2009). Indeed, McKenney (2018) notes: "Although many studies in the learning sciences describe potential implications of policy or practice, few elaborate on how recommendations can be implemented" (p. 1).

Specifically, as Wilcox et al. (2021) point out there continues to be a significant "research to practice gap". For example, Roediger (2013) writes:

> *We cannot point to a well-developed translational educational science in which research about learning and memory, thinking and reasoning, and related topics is moved from the lab into controlled field trials (like clinical trials in medicine) and the tested techniques . . . are introduced into broad educational practice. We are just not there yet . . .* (p. 1).

Furthermore, one of the nation's foremost education researchers and policy analysts, Linda Darling-Hammond, argues that the rapid pace of our knowledge of human development and learning has impacted the emerging consensus about the science of learning and increased our opportunities to shape more effective educational practices (Darling-Hammond et al., 2020). Yet, she adds, to take advantage of these advances requires integrating insights across multiple fields and connecting them to our knowledge of successful approaches.

In this perspective piece, we adapted a translational research model for the learning sciences to inform teachers, educational psychologists, and practitioners on benefits of Embodied Cognition (EC) and Embodied Learning (EL) applications for the classroom.

TRANSLATIONAL SCIENCE: THE NEED FOR A BRIDGE

Translational science research emphasizes a need for appropriate professional development that fosters interdisciplinary approaches (Gilliland et al., 2017) for quickly turning biomedical findings from the laboratory, clinic, and community into interventions to improve the health of individuals and the public (NCATS-NIH, 2020). That said, to meet the challenges of collecting and disseminating the latest cognitive-science empirical research on learning, we adapted a model of translational science (Rubio et al., 2010). We call our model the *Translational Learning Sciences Research* for Embodied Cognition and Embodied Learning[1]. Our model leverages the empirical findings on EC from psychology and learning theory to provide an overarching theory for why embodied-based learning works. The call for translational research for the benefit of education is not new, although the term *translational* has only recently been applied in fields other than the natural sciences[2]. Here, we provide a framework for why these examples work and what generalized learning principles can be derived from these examples to impart educators with useful practice. Our model curates EC research across multiple learning fields (e.g., STEM, reading/language, social-emotional learning) while focusing on how researchers are beginning to implement both low-stakes embodied learning activities in the classroom and also those based on sophisticated technologies of AR, VR, and mixed reality (step 1 and 2 of our model). Our model then extracts generalized EL principles that can be easily used in the classroom as a starting point for researchers, teachers, policy makers, and designers to work together (step 3) to help translate and disseminate the latest research and create validated learning platforms and activities based on EC principles (step 4). The goal is to accelerate the process of transforming laboratory discoveries into new pedagogical approaches to improve learning outcomes. Before we discuss the details of our model, however, we present a quick history of EC and EL and why it matters to education.

Rethinking Thinking

Over the last forty years there has been a paradigm shift in Psychology, in which human thinking is now viewed as inseparably linked with the body and the environment (e.g., Varela et al., 1991; Wilson, 2002; Abrahamson, 2004; Hutto, 2007; Chemero, 2009; Fugate et al., 2018). Embodied views of thinking suggest that it is deeply dependent on features of the physical body of the learner, where the body plays a significant causal or constitutive role in cognitive processing (Kumar, et al., 2018; Wilson and Foglia, 2011). Such embodied views of cognition are based on bodily and neural processes of perception, action, and emotion (e.g., Hauk et al., 2004; James, 2010; Vinci-Booher and James, 2020, to name a few). For example, research also shows that simply *observing* another's gestures and movements can activate the mirror neuron system in the learner's brain to aid in learning through imitation (Rizzolatti et al., 1996). This finding has led to the suggestion that the mirror neuron system may be the mechanism for imitative EC (Rizzolatti et al., 1996; Iacoboni et al., 2005; Iacoboni, 2009).

We owe a great deal to developmental psychologists whose theoretical insights are affirmed by the latest neuroscientific evidence (e.g., Piaget and Cook, 1952; Piaget, 1968; Montessori, 1969; Vygotsky, 1978; Kolb, 1984; Dewey, 1989; Rogoff, 1990). Indeed, Vygotsky (1926/1997) wrote: "Thought is action … your capacity to enact the concept as perceptuomotor activity" (pp. 161–163). Philosophically, Merleau-Ponty (1962) posited that people perceive the world first and foremost through their bodies, a type of inter-corporeality which he referred to as "enfleshment."

Although there are many theories of EC, all are united in their emphasis on the body and draw upon two common themes. First, the body and the world (environment) are integral to forming, integrating, and retrieving knowledge. To that end, knowledge is *grounded* or *situated* in the interactions between the individual and the environment. *Grounding* might occur when words or linguistic

[1]Steps adapted from the National Institutes of Health NCATS (2020) and Rubio et al. (2010).

[2]For example, in 2015 APA launched a new journal called Translational Issues in Psychological Science. In 2015, Kaslow identified "Translating Psychological Science for the Public" as one of her APA presidential initiatives, and appointed a task force to develop new strategies to communicate psychology to the public, with the idea that psychology can one day resemble the public's knowledge of—and demand for—medical information.

metaphors bind together individual, heterogenous instances underlying abstract concepts (Lakoff and Johnson, 1980; Mazzuca and Borghi, 2019)[3]. Second, knowledge is *simulated*: Thinking, or the *use* of knowledge, is re-experiencing the bodily states that were activated at the initial time of encoding, as experienced by a person's individualized interactions with the world (Barsalou, 1999; Barsalou, 2008; Gallese, 2009).

Recently, EC has expanded its reach into "4E cognition", which suggests people's cognitive activity is not only embodied, but also "extended, enacted, and embedded" in the perceptual and interactive richness of their environment (see Gallagher in Rowlands, 2010). Abrahamson et al. (2021) advanced Enactivism (Varela et al., 1991) as a philosophical framework that captures "thinking as situated doing" for classroom learning. The emphasis is placed on *students' experience* as their source knowledge rather than on the teacher transmitting content (Petitmengin, 2007). For example, a learner and their surrounding environment constitute a system, in which the learner's thoughts, actions, and metacognitive awareness/ verbalizations (Flavell, 1979; Bernstein, 1996) may promote the discovery of new relations between their body and environment (Suwa, 2006).

BOTH TEACHING AND LEARNING NEED TO BE RE-EXAMINED

Our current educational delivery systems (i.e., teacher education, pedagogy, curriculum) and approaches can be traced back to "disembodied" views of human thinking. Specifically, much of teaching pedagogy/curriculum continue to view learning as abstracted and separate from the body (Macrine, 2002) and fails to understand the latest psychological and neuroscientific evidence from EC. Similarly, teacher training/pedagogy, while emphasizing constructivist's approaches, tends to devolve-in-practice to positivist's skills in preparation for standardized tests (Klein et al., 2019). According to Nathan (2012), teaching continues to focus on foundational knowledge or "formalism first". Specifically, formalism first "incorrectly advocates the teaching/mastery of formalisms often considered prerequisite to applied knowledge" [that] "privileges formal, scientific knowledge over applied knowledge" (Nathan, 2012, p.126). Further, Nathan asserts that formalisms only gain their meaning with embodied experiences through real-world interaction and therefore the experiences are what ground formalisms, not the other way around. Similarly, Wertsch (1985) noted that a construct is shared when the action and affordances are experienced with the adult and contextualized in the real world.

Rethinking Learning

Derived from EC principles, EL constitutes a contemporary pedagogical theory that emphasizes the use of the body in educational practice, as well as student-teacher interaction both in and outside the classroom (Smyrnaiou and Sotiriou, 2016; Kosmas and Zaphiris, 2018; Georgiou and Ioannou, 2019). EL posits that a person's own actions (and the observation of others' actions) interact with environmental affordances, and together scaffold the process of learning.

While EC uses similar approaches to active learning, EL includes a variety of body-based techniques (i.e., gestures, imitations, simulations, sketching, and analogical mapping) (Alibali and Nathan, 2007; Weisberg and Newcombe, 2017) that hold promise for understanding the role of action and experience in early development, as well as to scaffold learning in more formal educational settings (Kontra et al., 2012). Following suit, embodied design is a pedagogical framework that "seeks to promote grounded learning by creating situations in which students can be guided to negotiate tacit and cultural perspectives on phenomena under inquiry" (Abrahamson, 2013, p. 224).

OUR MODEL: TRANSLATIONAL LEARNING SCIENCES RESEARCH FOR EMBODIED COGNITION AND EMBODIED LEARNING

In light of recent empirical demonstrations of how EC/EL works, our model of *Translation Learning Sciences Research* for Embodied Cognition and Embodied Learning has seven goals: 1) making sense of and disseminating clinical and empirical research findings; 2) closing the gap between research and application; 3) combining cognitive science and pedagogy to share pertinent information; 4) improving teaching and learning through embodied applications; 5) confirming or debunking current trends, (i.e., neuromyths); 6) elucidating conceptual frameworks for sensorimotor and body-based learning; and 7) recommending curriculum, designs, taxonomies, technology, and development to inform policy.

From these goals, we outline the following four action steps: 1) Promote the multidirectional and multidisciplinary integration of basic embodied research to elucidate or to debunk current trends in teaching and learning; 2) Compile the embodied research to be analyzed, translated, and make connections to improve pedagogical approaches, with the long-term aim of improving teaching and learning; 3) Develop and disseminate resources and tools to help individuals at all levels of expertise develop a better understanding of EL; 4) Focus on the creation of appropriate embodied curriculum and the development of taxonomies to identify objectives, and track outcomes that will assess whether program objectives and competency requirements are being met. We believe that our model can serve as an expeditious way to systematically collate, translate, and disseminate the latest embodied research geared towards improved learning outcomes. In other words, this is where science meets the real world of schooling.

In a larger research project, we have addressed steps 1 and 2 by carefully curating examples from leading experts to show how EC can be integrated into classroom practice (Macrine and Fugate, 2020). Such research examples are based on behavioral and neuroimaging experimentation in the fields of language and reading comprehension, STEM, and social-emotional knowledge. By way of a few noteworthy examples, Kiefer et al.

[3]Other theories suggest that there is no grounding necessary because there are no mental representations (Gallagher, 2005; Hutto, 2005; Thompson, 2007; Chemero, 2009; Hutto and Myin, 2012; Hutto and Myin, 2017).

(2015) found that young students who relied on physically writing (compared to typing) had improved word reading and word writing. James (2010) found that four-to-five year-old participants, who had practiced writing letters through handwriting (but not other ways), showed adult-like brain activation when subsequently viewing letters. Further, college students demonstrated better recall of handwritten notes vs. typed notes (Mangen et al., 2015). In addition, Glenberg and colleagues (Glenberg and Kaschak, 2002; Glenberg et al., 2008; Glenberg and Gallese, 2012) showed how vocabulary acquisition can be enhanced by shared communication and physical pantomime, both which allow for the grounding of information to concrete objects. In another example, Boaler and colleagues (Boaler et al., 2016) demonstrated how finger perception predicted learning math all the way through college, and that young children with good finger-based numerical representations showed better arithmetic skills. In addition, the panoply of motion-based technologies and interactive-user gaming platforms have allowed VR and AR designers to create technology-enabled EL experiences. Such technologies range from gesture-based to full-body interactive technologies, with the latter making up fewer options and focusing mainly on VR and AR technologies (Trninic and Abrahamson, 2012; Johnson-Glenberg, 2018; Georgiou and Ioannou, 2019).

Several of these researchers, and numerous others working within the field of learning design and practice, have turned such research findings into EL technologies for the classroom. As an example, the M*oved by Reading approach* uses simulation or "acting-out" in two stages to enhance reading (Glenberg et al., 2004). In the first stage, called *physical manipulation*, children manipulate toys to simulate the story that they are reading. The second stage is called *imagined manipulation*, where children are taught how to mentally simulate or imagine doing the actions. The authors found that physical and imagined manipulations contributed to larger gains in memory and comprehension than dis-embodied reading approaches. Gomez and Glenberg (2022) demonstrated the importance of pantomiming while reading new physics content. Abrahamson and colleagues designed multiple, successful embodied instruction design applications, called Mathematical Imagery Trainers (MITs). In one high technology-based project known as the *Kinemathics* project (Abrahamson et al., 2011), students move their arms in proportional distances to measurements of similar magnitude displayed on a screen. Using a trial-and-error approach, correct answers turn the screen green and incorrect ones turn it red, which reinforces the rules underlying the relationship (i.e., a 1:2 rule). And, in another specialized application, Abrahamson and Lindgren (2014) developed *MEteor,* an interactive MR simulation that uses a laser and floor-projected imagery. In this application, students use their bodies to simulate an orbit around a virtual planet to learn about formal concepts such as gravitational acceleration and mass.

Perhaps just as important is that many of these applications can be adapted to students with learning disabilities. Indeed, advances in EL have been utilized with students with ASD (De Jaegher, 2013; Eigsti, 2013; Eigsti, 2015), deaf students, and students with motor impairment (Kosmas et al., 2019; Tancredi et al., 2022).

In the remainder of this perspective, we focus on steps 3 and 4 of our model. Step 3 advocates for a coordinated effort - a type of interactive educational/cognitive-science consortium - among researchers, educational psychologists, teachers, school psychologists, policy makers, and textbook publishers to translate and disseminate/share the latest findings, applications, and implementation of the latest developments. These include bringing such issues to the attention of: 1) university-affiliated design-based research laboratories; 2) school personnel–primarily teachers but also technology experts and principals; 3) parents—as individuals and *via* various organized bodies–invested in school policy on infrastructure, resources, and pedagogy; 4) non-profit education-promoting groups, who are hampered neither by publication nor sales constraints; 5) commercial educational-technology companies with forward-thinking strategies; and 6) reporters, bloggers, etc. who cover the educational beat and can bring these issues to the attention of the wider public, including city, state, and federal policymakers. These many—and in rare occasions collaborations among them—could hasten the experimental application of cutting-edge research in the form of convivial instructional resources. For example, a national database of open-science materials and data could be coordinated to allow any teacher to use the materials and to contribute to "open science", which has become popular already in psychology[4].

To begin to address step 4, we have extracted the following key appropriate embodied principles (**Table 1**) for future practitioners, researchers, and teachers to guide the research-to-practice transition.

The final step will be for educators and policy makers to use these principles to develop taxonomies of embodied curriculum, identify learning objectives and outcomes, and track outcomes to assess whether program objectives and competency requirements are met. Specifically, "*in situ*" assessments will be needed, as retrospective measures of learning (e.g., written tests, etc.) are at odds with the very nature of EL (Georgiou and Ioannou, 2019). As Roschelle et al. (2011) point out: "Meaningful educational change almost always involves coordinating and aligning related changes (e.g., in curriculum, technology use, pedagogy, assessment, and school leadership)" (p. 33).

SUMMARY AND FUTURE DIRECTIONS

Our *Translational Learning Sciences Research* for Embodied Cognition and Embodied Learning came about because there is a need for an expeditious pipeline to get the latest cognitive science and empirically validated educational applications out to the public. Our model provides a bi-directional conduit in which research findings and applications can flow quickly. We are advancing our model as a vehicle to continue to collate vetted examples of EL as they relate to EC theory. Our model is aimed at informing EL in an earnest way through a translational science approach[5]. We hope that it encourages

[4]see https://www.apa.org/science/about/psa/2019/02/open-science.

[5]Such a "translation" of psychology research to classroom-practice has, however, been done for research on metacognition (Flavell, 1979) (e.g. Tanner, 2012; Beach et al., 2020). Beach and colleagues have an entire manual on the role of metacognition in teaching and learning, highlighting four key findings that are similar in effect to our extracted teaching principles for embodied cognition.

TABLE 1 | *Key Principles for Translational Learning Sciences Research for Embodied Cognition and Embodied Learning.*

EC principle and generalized advice	Domain	Scientific findings* = classroom-vetted K-12	Classroom resources/Links	Specific teaching principle
1) The use of body-based learning (i.e., sensorimotor learning, including using whole-body and fingers, and gesturing). Teachers should promote body-based learning, including self-generated actions involving touch, sight, drawing, and writing.	Reading	Vocabulary acquisition, reading comprehension skills, and cued and spontaneous recall rely on connecting linguistic elements (e.g., the words and phrases in the linguistic input) to sensorimotor capacity (e.g., the perceptual or motor skills to which those linguistic elements refer) [Glenberg and Kaschak (2002), Glenberg et al. (2004)*, Kaschak et al. (2005), Pulvermuller (2005), Glenberg et al. (2007), Marley et al. (2007)*, Glenberg (2008), Glenberg et al. (2009)*, Glenberg et al. (2011)*, Zwaan (2014), Kaschak et al. (2017)*].	*Embrace* and *Moved by Reading* programs https://www.movedbyreading.com/	Teachers can encourage word learning and language comprehension through: 1) dialogic reading, in which the adult asks questions related to the text that are intended to prompt dialogue; 2) "acting out" vocabulary or sentences through play with a physical representation of content depicted in the text; and 3) performing iconic actions to illustrate word meaning through gesture or pantomime.
—	Reading	Taking notes with pen and paper (vs. typing) encourages summative understanding because of the slowness (but also richness) of physically writing [Mueller and Oppenheimer, (2014)].	—	For language and material comprehension, teachers can encourage students to handwrite notes that are summative (and less dictated). Students' self-generated, summative arguments actions can be more powerful than memorization or writing notes verbatim.
—	Reading	Reading from print books (rather than digitally on computers or tablets) can enhance kinesthetic and tactile feedback and can improve information general comprehension. [Mangen (2008), Mangen et al. (2013)*, Delgado et al. (2018), Mangen et al. (2019)].	—	Teachers can encourage paper books or electronic reading displays (e.g. Kindle), which more closely simulate the physicality of print books, especially for longer passages.
—	Handwriting	Exploring letters visual-haptically (vs. visual only) improves handwriting and is important for letter learning and early literacy [Naka (1998)*, Longcamp et al. (2003), Bara et al. (2004)*, Longcamp et al. (2005), Longcamp et al. (2008), Mangen and Velay (2010), Bara and Gentaz (2011)*, James and Engelhardt (2012), Kiefer et al. (2015)*, Mangen et al. (2015), Mangen and Balsvik (2016), James (2017)].	—	Teachers can encourage learning to write by hand.
—	Math and Science	Finger use and perception predict mathematics achievement [Berteletti and Booth (2015), Boaler et al. (2016)].	YouCubed Team: https://www.youcubed.org/wp-content/uploads/2017/03/Finger-Activities-vF.pdf	Teachers can encourage solving mathematical problems with real-world objects, rather than solving comparable symbolically presented problems.
—	Math and Science	Mathematical attainment is related to interceptive timing ability and is learned through perceptually guided actions that instantiate the concept as a movement form [Abrahamson (2004)*, Abrahamson (2007)*, Gracia-Bafalluy (2008)*, Reinholz et al. (2010)*, Abrahamson et al. (2011)*, Abrahamson (2014), Abrahamson et al. (2014)*, Abrahamson and Trninic (2015)*, Giles et al. (2018), Abrahamson et al. (2020)].	3D Multiplication Table (Embodied Design Laboratory): https://edrl.berkeley.edu/design/3d-multiplication-table/ Math Imagery Trainers (MITs) MIT-Proportion and MIT-Parabola (Embodied Design Laboratory) https://edrl.berkeley.edu/design/mathematics-imagery-trainer/ *Kinemathics* (Embodied Design Laboratory): https://edrl.berkeley.edu/projects/kinemathics/ Combinations Tower (Embodied Design Laboratory): https://edrl.berkeley.edu/design/combinations-tower/ YouCubed Team: https://www.youcubed.org/tasks/ 4-Blocks NetLogo (Center for Connected Learning and Computer-Based Modeling) http://ccl.northwestern.edu/netlogo/docs/ Dice Stalagmite NetLogo (Center for Connected Learning and Computer-Based	Teachers can provide multi-dimensional experiences in mathematics, which include multiple opportunities to see and experience concepts through touch, sight, drawing, and writing in words.

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TABLE 1 | (*Continued*) *Key Principles for Translational Learning Sciences Research for Embodied Cognition and Embodied Learning.*

EC principle and generalized advice	Domain	Scientific findings* = classroom-vetted K-12	Classroom resources/Links	Specific teaching principle
			Modeling): https://ccl.northwestern.edu/netlogo/models/DiceStalagmite	
—	Math and Science	Human capacity to perceive the environment in new ways is predicated on learning to move in new ways because perception of scientific concepts is inherently for action [Mechsner et al. (2001), Alibali and Nathan (2012)*, Walkington et al. (2019), Nathan et al. (2020)].	Block Stalagmite (Embodied Design Laboratory): https://edrl.berkeley.edu/design/4-block-stalagmite/ The Eye Trick (Embodied Design Laboratory): https://edrl.berkeley.edu/design/the-eye-trick/ *MEteor: Developing Physics Concepts through Body-based Interaction with a Mixed Reality Simulation (Lindgren et al., 2016)* The Hidden Village: Mathematical Reasoning through Movement https://multiplex.videohall.com/presentations/1662 Magna-AR: https://www.vieyrasoftware.net/physics-toolbox-ar PhysicsToolbox: https://play.google.com/store/apps/details?id=com.chrystianvieyra.physicstoolboxsuite&hl=en_US HistoBlocks: https://ccl.northwestern.edu/netlogo/models/HistoBlocks The Marbles Scooper: https://edrl.berkeley.edu/design/the-marbles-scooper/ Data science K-12 initiative: https://www.youcubed.org/resource/data-literacy/ SMALLab Learning, LLC: https://www.smallablearning.com/research Ratio and Proportion (Phet Interaction Simulations): https://phet.colorado.edu/en/simulation/ratio-and-proportion.	Teachers can create conditions that enact movement that captures the dynamical sense of a concept.
—	Math and Science	Gestures are spontaneous or purposeful movements of the body that often accompany speech, serve as a way to convey ideas, and predict the quality of one's argument in mathematics and sciences (e.g. physics) [Kontra et al. (2015), Johnson-Glenberg et al. (2016)*, Johnson-Glenberg and Megowan-Romanowicz (2017), Johnson-Glenberg (2018), Megowan-Romanowicz (2022)].	—	Teachers can consider how gestures support understanding and reveal learners' struggles and understandings. Teachers can directly interact with learners' gestures when describing their embodied experiences with embodied learning technologies by: (1) pointing out/highlighting aspects of the gesture; and/or (2) contributing new dynamic gestural imagery to the gesture. Teachers can attend to not only what learners say, but also to learner's movements, idiosyncratic forms of perception, and how learners interpret their embodied experiences. Noticing these behaviors can help teachers prompt perceptual-motor activity at timely moments.
2) Imitative body-based learning from others, including attention to other's body movements. Teachers need to be attentive to students' whole-body learning	Socio-Emotional	Observational learning is important for acquiring and communicating knowledge. The mirror neuron system (MNS) responds robustly to observation and imitation of face and hand actions [Iacoboni et al. (2005), Immordino-Yang and Damasio (2007), Caspers et al. (2010), Caramazza et al. (2014), Aziz-Zadeh et al. (2018), Ferrari and Coudé		Teachers can engage in demonstrating a skill, and students should engage in subsequent imitation or emulation to enhance observational learning.

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TABLE 1 | (*Continued*) *Key Principles for Translational Learning Sciences Research for Embodied Cognition and Embodied Learning.*

EC principle and generalized advice	Domain	Scientific findings* = classroom-vetted K-12	Classroom resources/Links	Specific teaching principle
experiences and intentionally incorporate movement into learning activities, which can increase the connection between the physical environment and academic goals through situated learning. Teachers should assess students' developing understanding by attending to both their gestures and body language.		(2018), Keysers et al. (2018), Butera and Aziz-Zadeh (2022)].		
—	All	Students learn through repeatedly attempting to reconstruct actions performed by others, and follow action goals of others [Flanagan and Johansson (2003), Gerofsky, (2011)*, Hall and Nemirovsky (2012), Gredebäck and Falck-Ytter (2015), Vogelstein et al. (2019)].	—	Teachers can use goal-directed human movement to illustrate new concepts. Teachers can use simple bodily movements to help learners understand more advanced concepts (e.g., opposing forces as argument opposition) as they develop.
3) Responsive Teaching Teachers should support student engagement by monitoring what the individual is doing, encouraging them to come up with their own strategies and reflect.	Socio-Emotional	Teacher and students who engage in joint attention experience more positive affect, likely attributable to increased agency [Steinbrenner and Watson (2015), Grynszpan et al. (2017)].	—	Teachers can engage in joint attention with the student by encouraging collaborative situated interactions.
—	All	Intercorporeal attunement (i.e., responsiveness) is bidirectional, that is, students attune to teachers. In conversations, even multi-person discussions, speakers are constantly returning to each other. This is a rapid, iterative, and reciprocal process [Radford and Roth (2011), Shvarts and Abrahamson (2019)].	—	Teachers can create a classroom climate that encourages students to express and discuss how concepts "look," "move," "feel," etc. Teachers can make instructional decisions based on what they can *see* that was not understood.
—	All	Responsive teaching involves: 1) drawing out, attending to, and engaging with aspects of learners' ideas that have potential disciplinary value or substance; and 2) engaging in ongoing *proximal formative assessment* (e.g., continuously monitoring students' ideas to adapt instructional support in the moment) [Robertson et al. (2016), Flood et al. (2020), Flood et al. (2022)].	—	Teachers can try to reformulate learners' ideas to help them extend and connect these ideas with new disciplinary understandings. One way to achieve this is through the practice of *revoicing*, (i.e., recasting learners' multimodal contributions by repeating some content) yet also reformulating (modifying the content of) and/or elaborating (adding new content to) the ideas learners have shared.
—	Special Needs	Individuals with motor and sensory impairment will have different experiences over time that shape how they come to understand the world, mandating the need for including "inclusive design" [Ma (2017), Abrahamson et al. (2019), Chen et al. (2020), Tancredi et al. (2022)].	Balance Board Math (Embodied Design Laboratory/Tancredi: https://edrl.berkeley.edu/projects/balance-board-math/ Magical Musical Mat (Embodied Design Laboratory/Chen): https://edrl.berkeley.edu/projects/magical-musical-mat/ SignEd|Math (Embodied Design Laboratory/Krause): https://edrl.berkeley.edu/projects/signedmath/	
4) Use of manipulatives with relevant affordances (including AR/VR but also "simpler" actions)	All	Augmented reality (AR) technologies enhance and expand opportunities to learn through moving and can improve both visuospatial capabilities and enhanced student-reported interest leading to more	Titans of Space (Drash VR LLC): http://www.drashvr.com/titansofspace.html	Teachers can encourage the use of concrete manipulatives (e.g., blocks, chips, Dienes blocks, Geotiles, balance scales, paper clips, popsicle

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TABLE 1 | (*Continued*) *Key Principles for Translational Learning Sciences Research for Embodied Cognition and Embodied Learning.*

EC principle and generalized advice	Domain	Scientific findings* = classroom-vetted K-12	Classroom resources/Links	Specific teaching principle
Teachers should root themselves in practices that exemplify interaction that supports conceptual modeling, including digital simulations as well as physical manipulatives, especially for STEM fields.		accurate performance (vs. traditional instruction) [Carbonneau et al. (2013), Lindgren and Johnson-Glenberg (2013), Abrahamson and Lindgren, (2014), Donovan et al. (2014), Carbonneau and Marley (2015), Johnson-Glenberg et al. (2016)*, Lindgren et al. (2016)*, Johnson-Glenberg and Megowan-Romanowicz (2017), Vieyra et al. (2020), Donovan and Alibali (2021), Donovan and Alibali (2022), Megowan-Romanowicz (2022); Vierya and Vierya (2022)*].	Catch a Mimic (Embodied-Games.com): www.embodied-games.com	sticks, and beanbags) and computerized or AR technologies created and vetted for learning.
—	All	All technologies have their own material affordances and sensorimotor contingencies, which frame and constrain a person's interaction with a device [Gibson (1979), Gaver (1991), Kamii et al. (2001), Moyer (2001)].	—	Teachers can consider the following when deciding whether and how to use a given manipulative: 1) identifying the target concept, considering how the object under consideration relates to the target concept; 2) considering what actions the object affords; and 3) considering how those actions relate to the target concept.
—	All	Manipulatives are most effective when their design enables students forms of sensorimotor *engagement* that prompt diverse ways of reasoning related to the content, as well as *coordinating* among these different ways of reasoning [Abrahamson et al. (2014)].	—	—
5) Bodily-based sensory awareness of internal states Teachers should encourage students to express pride, enjoyment, and hopes about their learning, and engage in positive attitudes about the efficacy of body-based learning.	Socio-Emotional	Body-based approaches and therapies which lead to the disambiguation of affective states can improve emotion regulation and perception of emotion, as well as improve attention and performance in the classroom [O'Conner et al. (2017), Jagers et al. (2019)].	CASEL: https://casel.org/resources/	Teachers can capitalize on teaching emotion vocabulary and mindfulness to individuals to not only improve emotional interactions and regulation, but also to improve attention, focus, and cognitive awareness, which all facilitate academic performance.
—	Socio-Emotional	Individuals higher in granularity report more flexible emotional regulation abilities [Barrett et al. (2001), Boden et al. (2012)], have a less reactive coping style [Tugade et al. (2004)], and are less biased by incidental emotions when making moral decisions [Cameron et al. (2013), Fugate and Wilson-Mendenhall (2022)].	—	Teachers can label student's emotional states and include socio-emotional learning (SEL) into the classroom. Emotions can be labeled and incorporated into the category knowledge about human behavior.
—	Socio-Emotional	Knowing one's own feelings may also help with understanding others' feelings [Saarni (1997)].	—	—
—	Socio-Emotional	The awareness practices that characterize mindfulness-based interventions are thought to improve emotion regulation by cultivating a more fine-grained awareness of what is occurring in one's mind [Hill and Updegraff (2012), Roemer et al. (2015), Carsley et al. (2018)].	—	Teachers can consider adding in mindfulness practices into the classroom.

cognitive science and educational researchers to offer and make their research available across the fields of educational psychology, educational policy, and teacher education to improve student outcomes and classroom pedagogy. We want to improve communication between scientists and practitioners and to avoid the occurrence of misconceptions, such as neuromyths to shape their pedagogies (Tan and Amiel, 2019). Our model was developed to reimagine how educators can access reliable research to inform their own pedagogy to create a more equitable and just schooling for all.

While we applied this new education-based translational research model to embodied cognition for teaching and learning, we believe that our model can also be used in different educational research contexts. Thus, this approach could provide a vehicle for the dissemination of theory-driven empirical findings translated into evidence-based classroom practice and enable bi-directional suggestions for future research, best practice, and theory development. Ultimately, the continued development of such pathways will lead to the advancement of—and efficient translation of—the latest cognitive science and educational psychology research findings for the educational community.

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SM and JF contributed to all aspects of the article including model development and writing, as well as approved the submitted version.

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