Metaphors Are Projected Constraints on Action: An Ecological Dynamics View on Learning Across the Disciplines

Dor Abrahamson, University of California, Berkeley, dor@berkeley.edu
Raúl Sánchez–García, Universidad Europea de Madrid, raulsangar@gmail.com
Cliff Smyth, Saybrook University, smythcliff@gmail.com

Abstract: Learning scientists have been considering the validity and relevance of arguments coming from philosophy and cognitive science for the embodied, enactive, embedded, and extended nature of individual learning, reasoning, and practice in sociocultural ecologies. Specifically, some design-based researchers of STEM cognition and instruction have been evaluating activities for grounding subject content knowledge in interactive sensorimotor problem solving. In so doing, we submit, the field stands greatly to avail of theoretical models and pedagogical methodologies from disciplines oriented explicitly on understanding, fostering, and remediating motor action. This conceptual paper considers potential values of ecological dynamics, a perspective originating in kinesiology, as an explanatory resource for tackling enduring Learning Sciences research problems. We support our position via an ecological-dynamics reexamination of the function of metaphor in the instruction of sports skills, somatic awareness, and mathematics. We propose a view of metaphors as productive constraints reconfiguring the dynamic system of learner, teacher, and environment.

Keywords: ecological dynamics, martial arts, metaphor, mathematics, music, somatic practice

Objectives: Bringing the body sciences into embodiment theory

The Learning Sciences are abuzz with federally funded research projects, special journal issues, symposia, workshops, and graduate-level reading courses all evaluating the putative embodied, enactive, embedded, and extended nature of individual cognition, learning, reasoning, and practice in sociocultural ecologies (Abrahamson & Eisenberg, 2012; Chandler & Tricot, 2015; Nathan, Alibali, Nemirovsky, Walkington, & Hall, 2015; Overton, 2012; Wilson & Golonka, 2013). This so-called "E-turn" in the Learning Sciences (*e*mbodied, *e*nactive, *e*mbedded, *e*xtended,…) has been contributing original critiques of long-held theoretical models and pedagogical assumptions underlying much educational scholarship and practice (de Freitas & Sinclair, 2014; Roth, 2015; Spackman & Yanchar, 2013). In turn, the E-turn is stimulating the design of new technological platforms (Lee, 2015), instructional activities (Lindgren & Johnson–Glenberg, 2013), and research methodologies (Worsley & Blikstein, 2014), including the use of multimodal data gathering and analytics for investigating the impact of multimodal tasks (Abrahamson, Shayan, Bakker, & van der Schaaf, in press).

By and large, these E-turn efforts have so far drawn and oriented on classical intellectual spheres, familiar educational spaces, and canonical domains of knowledge, skill, and intervention. Namely, most educational researchers who have been inspired by the E-turn are looking to the cognitive sciences, writ large, so as better to understand the potential role that overt or covert sensorimotor activity may play in the teaching and learning of language arts and STEM content (Enyedy, Danish, Delacruz, & Kumar, 2012; Glenberg, Willford, Gibson, Goldberg, & Zhu, 2012; Landy, Brookes, & Smout, 2014). We submit that the E-turn could bear an even greater impact on the Learning Sciences if the field considered additional intellectual disciplines and cultural practices. *In particular, we argue that educational researchers who are designing and evaluating instructional activities centered on students' motor actions should avail from engaging with empirically based robust theoretical models from disciplines that evolved explicitly so as to investigate and serve the development, practice, and remediation of human motor action*. By thus looking further afield, we argue, the field of the Learning Sciences stands to avail of theoretical frameworks that hitherto have played at best minimal roles in educational research yet are optimally poised to inform E-turn research. As a case in point, this exploratory conceptual paper will consider the potential value of ecological dynamics, a theoretical model originating in kinesiology and sports science, as an explanatory resource for tackling an enduring pan-domain LS research problem, the problem of how metaphors work in teaching and learning.

Metaphor appears to serve as an appropriate construct for investigating new horizons and resources for E-turn research. On the one hand, the analytic treatment of metaphor has for the main looked to traditional cognitive-science Cartesian epistemology (Ortony, 1993), namely the historical assumption that cognitive activity is inherent in propositional symbol processing located in a brain that is functionally isolated from its sensory input and action output. Even the cognitive-semantics theories of conceptual metaphor (e.g., Lakoff & Núñez, 2000) and conceptual blending (Fauconnier & Turner, 2002), which look to embodied situatedness as the roots of complex reasoning, have been critiqued as unfit to explain evidence of simple human interaction, learning, and development (Gibbs, 2011, 2014). That is, whereas conceptual metaphor/blending theory offers models for ontogeny and praxis that are compelling in their descriptive and diagrammatic clarity, these descriptions are not capturing the empirical reality of mundane immersive being, such as a student dyad working together on an instructional task. On the other hand, the imagistic, situated, and often multimodal and dynamical semantic features of metaphor apparently lend this linguistic phenomenon to alternative treatments grounded in non-dualist, post-cognitivist, anti-representationist epistemologies (Chemero, 2009; Hutto, Kirchhoff, & Abrahamson, 2015). As such, a focus on metaphor may enable us to judge what the body sciences, and in particular the theory of ecological dynamics, might add to mainstream perspectives in the Learning Science.

We are thus arguing for the application of theoretical frameworks from the motor-action sciences to the analysis of educational interactions, and we have selected metaphor as a phenomenal context for building this conceptual argument. We pursue this argument by way of examining the potential of ecological dynamics to illuminate the function of metaphors in three domains of instruction: sports skills, somatic awareness, and mathematics. We contend that ecological-dynamics treatments of instructional metaphor shed new light on its mechanism, function, and effect on learning. In particular, we will propose a view of metaphor as a type of productive constraint projected into the environment. Instructors communicate metaphors verbally—often orally and gesturally, in close, real-time responsive coaching interaction—with the purpose of steering students to modify their engagement in a problem space. Making sense of verbal content is necessarily a tacit sensorimotor process of generating covert spatial–dynamical imagistic structures (Glenberg & Kaschak, 2002). These phenomenological entities are either anchored in actual environmental features or constitute new gestalts superimposed onto the environment ("projections," Kirsh, 2013). From the ecological-dynamics view, we theorize these induced structures as productively constraining students' process of solving a motor-action problem of practice. Given these new constraints, students must readapt to the changed environment so as to continue seeking to satisfy their assigned objective. They do so by developing new goal-oriented motor-action coordinations better suited to the modified circumstances. These coordinations are precisely the instructor's target learning outcome for the activity. In domains of conceptual learning, such as mathematics, these new coordinations are then encapsulated via reflection, semiosis, and discourse to take form as the target content.

Theoretical framework

Instructional metaphors—limitations of current theory

When a violin teacher asks a student to play a musical phrase as though she is throwing a ball into a basket, how does that instructional intervention result in a modification in her playing (see https://www.youtube.com/watch?v=st4-CcO4XwM, focusing on 01:53 – 03:14; see Figure 1)?

Figure 1. Emerging artist Mártha Déak (on left) in masterclass with Maestro Maxim Vengerov (on right), working on Mozart's Concerto No. 3 in G Major K216. Vengerov suggests Déak play the very first two notes of the violin part as though she is throwing a basketball into the basket—"tee-*yum*… tum!"

Common theoretical models treating the curious phenomenon of metaphor will have us believe that the student internally builds structural alignments between source and target domains—between the imagined actions of throwing a basketball and the imagined actions and audiated effects of generating a musical phrase—and then externally performs the intact conceptual blend of these imagined actions (Fauconnier & Turner, 2002; Lakoff & Johnson, 1980; Miller & Williams, 2010). We view these explanations as problematic, because they: (a) rely on a cognitivist perspective that assumes a mind–body duality comprising internal representations in the head that are implemented externally via the body into the environment—a view that jars with philosophical arguments (Phenomenology, Merleau–Ponty, 2005/1945; Enactivism, Varela, Thompson, & Rosch, 1991) cognitive-developmental psychology theory (genetic epistemology, Piaget, 1968), and cognitive-psychology empiricism (Hauk et al., 2004); (b) ignore the dynamical, interactive, developmental, and sociocultural facets of human experiences (Becvar et al., 2010; Malafouris, 2013); and (c) are not conducive to empirical evaluation (Gibbs, 2011, 2014). What might an E-turn model of instructional metaphors look like?

Ecological dynamics

Research on embodiment has recently been discussed in the sports sciences from a Radical Enactive Cognition perspective (Hutto & Sánchez–García, 2015) building upon the research program of ecological dynamics. The *ecological-dynamics* research program (Vilar, Araújo, Davids, & Renshaw, 2012) blends *dynamic systems theory* (Thelen & Smith, 1994) and *ecological psychology* (Gibson, 1966) enabling sports scientists to explain the learning of physical activities as the self-organizing of subject–environment dynamical complex systems. The ecological-dynamics perspective conceptualizes human learning not as hermetic process in an individual's head but rather as an entire system tending toward new task-satisfying dynamical equilibrium among the individual (the student) and the environment, where the environment may include natural and artifactual materials that may extend the student's reach. The system may include also fellow students, who may engage in the collaborative co-enactment of the new practice, and a coach, whose role is modeled as follows.

Whereas human agents engaged in goal-oriented activity constitute a self-organizing dynamical system, still their behavior can be affected or "channeled" by introducing various types of constraints (Araújo & Davids, 2004, p. 50). It may be useful to iterate that the term 'constraint,' which is used colloquially to negatively value an undesirable impediment to action, here signifies a positively valued discovery or intervention that blocks out the myriad ineffective engagement options and thus steers the novice closer toward the possibility of engaging effectively. Notwithstanding, though, and regardless of the source or type of constraint, it is ultimately the novices who, within the envelope of constraints, must develop situated sensorimotor schemes appropriate to achieving the task objective under shifting circumstances. A constraint-led model frames the *non-linear pedagogical approach* to sports, based on introducing and modifying constraints in the learning environment (Davids, Button, & Bennet, 2008; Renshaw, Chow, Davids, & Hammond, 2010). Non-linear pedagogy offers coaches and athletes a viable alternative to direct instruction. Individual athletes are explicitly encouraged each to discover their own motor-action coordination solution through goal-oriented physical activity within an appropriately constrained learning environment. Empirical evaluation of constraints-led, discovery-based learning has demonstrated its effectiveness and advantages (e.g., in skiing, Vereijken & Whiting, 1990).

To the extent that constraints are instrumental to the phenomenon of learning, they become important in research on learning. For researchers attempting to model learning as the emergence of agents' adaptive behaviors it has been useful to identify, articulate, and classify these various constraints. The leading kinesiologist Newell (1986, p. 404) identified three sources of constraints on the learning process: organism (biochemical, biomechanical, neurological, and morphological levels), environment (e.g., gravity, temperature), and task (goals and rules). Of these three sources of constraints, our interdisciplinary study focuses on the environmental, which in turn includes the subcategory of *augmented information*—a real-time instructional intervention, such as a teacher's responsive suggestions on how the student should modify her performance (Newell, 1996, pp. 422-423). From the ecological-dynamics perspective, the teacher's proactive, formative evaluation of students' suboptimal performance is thus conceptualized as introducing a productive constraint.

Augmented information comes in a variety of modalities, including speech, gesture, and/or visual materials, but also direct physical contact. To the best of our knowledge, scholars of constraint-based pedagogy have not looked at augmented information communicated via metaphor or simile. We propose a theoretical contribution centered on clarifying the systemic function of augmented information delivered via metaphor or imagistic instruction. To emphasize, from an ecological-dynamics perspective we view the potential effect of instructional metaphor as productively constraining the learner's solving of a motor-coordination problem.

Instructional use of metaphors, analogies, and similes has been documented in various sports branches (Masters, 2000; Lam, Maxwell & Masters, 2009). Yet it extends to other *overtly* embodied physical practices, such as dance (Bernard et al., 2006; Böger, 2012; Franklin, 1996; Kolter et al., 2010). For example, a variety of metaphors are used in a somatic practice called the Feldenkrais Method (Buchanan & Ulrich, 2001; Feldenkrais, 1972). Yet metaphor is prevalent also in the *covertly* embodied conceptual disciplines, such as mathematics (Abrahamson, Gutiérrez, & Baddorf, 2012; Núñez, Edwards, & Matos, 1999; Presmeg, 2006; Sfard, 1994).

Modes of inquiry: Comparing cross-domain paradigmatic cases

We three authors are bringing to bear theoretical constructs from our respective domains of investigation—mathematics, sports, and movement-based awareness ('somatic') practice. Acknowledging the obvious surface differences of these domains, our collaborative rationale here is to transcend these differences so as to articulate and refine a model at a semantic level that is general enough to illuminate phenomena in the three domains but not so general that it loses practical traction in any domain. Not an empirical study, this conceptual essay is more so a collective thought experiment examining the utility of the body sciences for the learning sciences.

Evidence: Ecological-dynamics analyses of instructional metaphors across three domains

We now present relevant case studies on the use of metaphors within didactical practices from our respective domains of investigation: martial arts (judo), mathematics (algebra), and somatic practice (Feldenkrais Method).

Case 1: Judo

Harai Goshi ("sweeping hip-throw") is a widely known and often used judo coordination pattern for overcoming an aggressor. A superficial view of Harai Goshi might focus primarily on the leg action that "sweeps" the opponent off the ground. A systemic perspective, however, describes the coordination pattern as a "balance scale falling out of balance" (Sánchez–García & González, 2014). This metaphorical visualization of a Harai Goshi performance may not be available to a novice onlooker, and yet it is instrumental to successful replication of the coordination pattern. Therefore, instructors attempt to foster this visualization via coaching intervention.

Figure 2 shows a male judoka performing Harai Goshi. The judoka is leaning his torso forward so as to counter-lever the other end of the embodied beam that sweeps up the opponent toward horizontal orientation, at which point he will rotate and fling the opponent over and onto the ground. As such, a judo sensei is likely to offer a judoka who is practicing Harai Goshi the metaphorical transition information, "Add weight to tip the balance beam out of balance" (Sánchez–García & González, 2014). If he accepts this augmented information, the judoka projects it onto his systemic field of action, which includes the opponent, as a new environmental constraint that he must comply with in order to complete the task of overthrowing the opponent. Initially, this new metaphorical image may disequilibrate and unpack the judoka's (ineffective) motor action coordination. With practice, though, he may figure out a new coordination that engages this image as an affordance for solving the problem. Reaching expertise, the judoka need no longer invoke the image, because the coordination becomes for him second nature. Unless he coaches others with the same image, he might forget it completely.

Figure 2. Instructional use of the "balance beam scale" metaphor in judo (sport)

Case 2: Mathematics

The mathematical subject matter of algebra presents many difficulties to students, including the notion of a variable as well as its symbolic notation in alphabetical characters (e.g., *x*, Kieran, 2007). A common curricular sequencing from arithmetic to algebra inflicts further cognitive entailments (Herscovics & Linchevski, 1996). In particular, novices to algebra are required to replace an *operational* conceptualization of the equal sign, as in "3 + 6 = ___ [solve!]", where the "=" denotes an imperative to perform arithmetic operations on the left wing of the equation and write the result on the right, with a *relational* conceptualization, as in "$3x + 6 = 4x + 2$", where neither of the two equivalent expressions on either side of the "=" is temporally antecedent to the other, the entire proposition does not bear any particular directionality, and it is not initially clear what operations should be carried out (Jones, Inglis, Gilmore, & Evans, 2013).

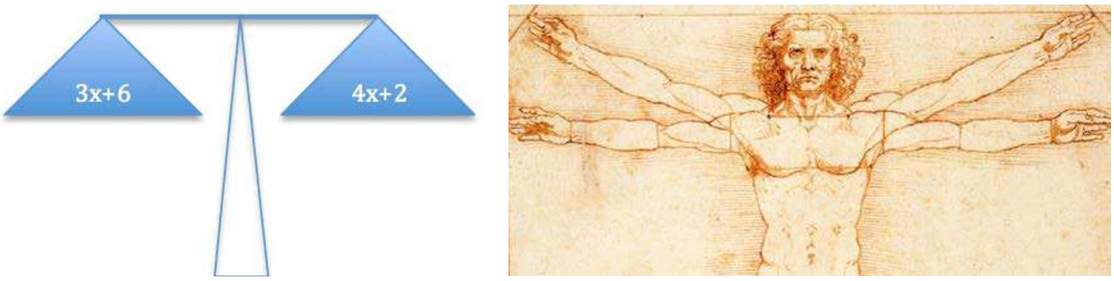

Figure 3. Instructional use of the "balance beam scale" metaphor in algebra (mathematics) juxtaposed with a fragment from da Vinci's Vitruvian Man as illustration for the intended embodiment of balance images.

From the ecological-dynamics perspective, the phenomenon of metaphorical visualization and engagement is conceptualized as a system composed of an organism (the algebra novice), a task ("solving for *x*," i.e. the task of determining the numerical value of the variable), and an environment (the manifold ecology in which the organism is to complete the task). Algebra novices are viewed as impeded by contextually inappropriate environmental constraints that they themselves are projecting into the field of action, namely the operational visualization. That is, students' robust arithmetic coordination patterns pre-constrain them to engage and manipulate features of the visual display in ways that block their access to a critical task-relevant affordance of the algebraic equation. The instructor who discerns behavioral evidence of the student applying these less effective constraints intervenes by offering alternative environmental constraints, and specifically by augmenting the algebraic proposition with the balance-beam structural dynamics (see Figure 3).

In passing we wish to stress from an enactivist perspective (Varela, Thompson, & Rosch, 1991) that "visualization," a term oft used in mathematics-educational research, tacitly enfolds action in addition to perception: To visualize is necessarily to see-for-acting, even if the perception never results in overt manipulation (Abrahamson, Lee, Negrete, & Gutiérrez, 2014); even when the symbols are inscribed on paper and therefore cannot be manipulated literally but only virtually (Landy, Brookes, & Smout, 2014).

Case 3: Feldenkrais Method

A common problem in human movement is how to enhance the efficient, comfortable, and safe use of the spine. This is not just a question of anatomy and physiology alone, as human movement is learned from infancy in the context of the community's "form of life" for the individual (e.g., task demands, socio-cultural practices, the material–cultural environment; Rietveld & Kiverstein, 2014, p. 327). The most efficient movement of the spine involves the distribution of force and movement through the spine according to its overall shape, the structure of the vertebrae, and their relationships.

Figure 4. 'Spine like a chain' (illustration picture with superimposed image of a chain).

The overall pedagogical strategy here may be viewed via ecological-dynamics as including organism (the Feldenkrais student), environment (mat, clinic), and task (lifting the pelvis with the legs in a comfortable, efficient, and effective way). Feldenkrais pedagogy directs the learners' attention to environmental constraints (gravity, surfaces, space), the changing relationships of/in the learner's body, and felt qualities of action (effort, smoothness, reversibility). This "education of attention" (Gibson, 1966, p. 52) creates a 'felt difference,' which the student can utilize to produce more effective patterns of action (Ginsburg & Schuette–Ginsburg, 2010).

Feldenkrais teachers use instructional metaphors, whether mathematical, geometrical, spatial, mechanical, or imagistic, and these are believed to induce "global process gestalts or vitality contours," "force-dynamic gestalts," "causal ("if-then") imagery," and salient "node points" (Kimmel, Irran, & Luger, 2014, p. 17; see also Smyth, 2012). In particular, a teacher may suggest the student imagine the 'spine as a chain' (see Figure 4). The chain is a simple and well-known implement that transmits and shapes forces through the action of its links and articulations. It 'maps' well onto the structure and function of the human spine. With a student lying on their back, both knees bent and lifting their pelvis, the image of the 'spine as a chain' can be used to invite the student to constrain the movement of the spine (e.g., aiming to lift or lower one vertebrae, or 'link,' at a time). If the student accepts the suggestion to utilize the image, there is a tactile and haptic 'sensing-for-action,' as suggested by the enactivist perspective—a new anticipatory 'feeling-for' changing pressure in relation to the floor. In turn, the points of pressure of the vertebrae against the floor now become salient points of information. The movement itself may alter into a punctuated or step-like pattern, link by link, to better sense how the spine articulates in relation to the floor. Now physical effort-force (perceived muscular effort, pressure in joints and on feet) and spatial-movement dynamics (the height of the pelvis and parts of the spine) are modulated to implement this metaphorical image of the spine-as-a-chain in the learner's action. This use of augmented information may thus afford a more differentiated and efficient use of the spine as well as an ability to sense the spine in a more differentiated way, potentially modifying future performance of this as well as related actions.

Conclusions and implications: A call to action

This explorative paper set out to consider whether theories originating in scholarship explicitly dedicated to motor development and control could contribute to educational research on teaching and learning in the disciplines (see also Beilock, 2008). Our motivation for this exercise was an assumption that motor-action models and methods should be relevant to any educational research program oriented on understanding the physical–dynamical roots of skill development, whether said skill is overtly embodied (e.g., surfing) or covertly embodied (e.g., physics). In particular, if we lay such stakes in the sensorimotor grounding of STEM concepts, it might behoove us to understand how sensorimotor activity is orchestrated with designed 'fields of promoted action' (Reed & Bril, 1996). Our rationale for this exercise was to: (a) select some motor-action theory; (b) identify an action-related pedagogical technique as a context for exploring the utility of the theory; (c) find appropriate paradigmatic phenomena from across the overtly and covertly embodied practices so as to test the robustness of this utility; and (d) evaluate for functional parity revealed across the practices via applying the theory. We chose the theory of ecological dynamics (Vilar et al., 2012) and its attendant constraints-led pedagogy (Davids et al., 2008; Renshaw et al., 2010), which originate in kinesiology and sports science, to examine the function of metaphor-based instructions across cases of martial-arts, mathematical, and somatic-rehabilitation practice. Our comparison suggested analogous educational process across the diverse disciplines.

This essay is no more than a Gedankenexperiment—we did not provide empirical data to support our claim. Nevertheless, we hope to have stoked a conversation on the potential of movement sciences to inform educational research. In particular, juxtaposing cases from covert and overt movement learning may sensitize educational researchers interested in STEM domains to invisible processes at play. Future empirical work may investigate the semiotic–somatic–semiotic processes putatively at play as students receive lexical information, enact it sensomotorically, and then reflect on this experience and document it using symbolic notation.

The hypothesis that instructional metaphors operate as productive constraints that learners project unto their task engagement could bear far-reaching implications for educational theory and practice. In particular, a proposal that learning across the disciplines is mobilized by projected imagery leads to an intriguing speculation: Some aspects of human reasoning in general could be modeled as the tentative projection of imagistic constraints on embodied cognitive actions. The very fundamental psychological construct of a frame could be recast from a dynamical-systems view as a constraint projected into a field of action. If learning is moving in new ways, so should the science of learning (Abrahamson & Sánchez–García, in press).

References

Abrahamson, D. (Chair & Organizer) & M. Eisenberg (Discussant) (2012). You're it! Body, action, and object in STEM learning. In J. v. Aalst, K. Thompson, M. J. Jacobson, & P. Reimann (Eds.), *Proc. of the 10th Int. Conf. of the Learning Sciences: Future of Learning* (Vol. 1, pp. 283-290). Sydney: ISLS.

Abrahamson, D., Gutiérrez, J. F., & Baddorf, A. K. (2012). Try to see it my way: The discursive function of idiosyncratic mathematical metaphor. *Mathematical Thinking and Learning, 14*(1), 55-80.

Abrahamson, D., Lee, R. G., Negrete, A. G., & Gutiérrez, J. F. (2014). Coordinating visualizations of polysemous action: Values added for grounding proportion. *ZDM Math. Education, 46*(1), 79-93.

Abrahamson, D., & Sánchez-García, R. (in press). Learning is moving in new ways: The ecological dynamics of mathematics education. *Journal of the Learning Sciences*.
Abrahamson, D., Shayan, S., Bakker, A., & Van der Schaaf, M. F. (in press). Eye-tracking Piaget: Capturing the emergence of attentional anchors in the coordination of proportional motor action. *Human Development*.
Araújo, D., & Davids, K. (2004). Embodied cognition and emergent decision-making in dynamical movement systems. *Junctures: The Journal for Thematic Dialogue, 2*, 45-57.
Becvar Weddle, L. A., & Hollan, J. D. (2010). Scaffolding embodied practices in professional education. *Mind, Culture & Activity, 17*(2), 119-148.
Beilock, S. L. (2008). Beyond the playing field: Sport psychology meets embodied cognition. *International Review of Sport and Exercise Psychology, 1*(1), 19-30.
Bernard, A., Steinmüller, W., & Stricker, U. (2006). *Ideokinesis: A creative approach to human movement and body alignment*. Berkeley, CA: North Atlantic Books.
Böger, C. (2012). Metaphorical instruction and body memory. In S. Koch, T. Fuchs, M. Summa & C. Müller (Eds.), *Body memory, metaphor and movement* (pp. 187-199). Amsterdam: John Benjamins.
Buchanan, P. A., & Ulrich, B. D. (2001). The Feldenkrais Method: A dynamic approach to changing motor behavior. *Research Quarterly for Exercise and Sport*, *72*(4), 315-323.
Chandler, P. & Tricot, A. (Eds.) (2015). Human movement, physical and mental health, and learning [Special issue]. *Educational Psychology Review, 27*(3).
Chemero, A. (2009). *Radical embodied cognitive science*. Cambridge, MA: MIT Press.
Davids, K., Button, C., & Bennet, S. (2008). *Dynamics of skill acquisition: A constraints-led approach*. Champaign, IL: Human Kinetics.
Enyedy, N., Danish, J. A., Delacruz, G., & Kumar, M. (2012). Learning physics through play in an augmented reality environment. *Int. Journal of Computer-Supported Collaborative Learning, 7*(3), 347-378.
de Freitas, E., & Sinclair, N. (2014). *Mathematics and the body: Material entanglements in the classroom*. New York: Cambridge University Press.
Fauconnier, G., & Turner, M. (2002). *The way we think: Conceptual blending and the mind's hidden complexities*. New York: Basic Books.
Feldenkrais, M. (1972). *Awareness through movement*. San Francisco, CA: Harper San Francisco.
Franklin, E. (1996). *Dance imagery for technique and performance*. Champaign: Human Kinetics.
Gibbs, R. W. (2011). Evaluating Conceptual Metaphor theory. *Discourse Processes, 48*(8), 529-562.
Gibbs, R. W. (2014). Why do some people dislike conceptual metaphor theory? *Journal of Cognitive Semiotics, 5*(1-2), 14-36.
Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.
Ginsburg, C., & Schuette–Ginsburg, L. (2010). *The intelligence of moving bodies: A somatic view of life and its consequences*. Santa Fe, NM: AWAREing Press.
Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review, 9*(3), 558-565.
Glenberg, A., M., Willford, J., Gibson, B., Goldberg, A., & Zhu, X. (2012). Improving reading to improve math. *Scientific Studies of Reading, 16*(4), 316-340.
Hanna, T. (1986). What is somatics? *SOMATICS: Magazine-Journal of the Bodily Arts and Sciences, 5*(4). Retrieved from http://somatics.org/library/htl-wis1
Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron, 41*(2), 301-307.
Hutto, D. D., Kirchhoff, M. D., & Abrahamson, D. (2015). The enactive roots of STEM: Rethinking educational design in mathematics. *Educational Psychology Review, 27*(3), 371-389.
Herscovics, N., & Linchevski, L. (1996). Crossing the cognitive gap between arithmetic and algebra. *Educational Studies in Mathematics, 30*(2), 39-65.
Hutto, D. D., & Sánchez-García, R. (2014). Choking RECtified: embodied expertise beyond Dreyfus. *Phenomenology and the Cognitive Sciences*, *14*(2), 309-331.
Jones, I., Inglis, M., Gilmore, C., & Evans, R. (2013). Teaching the substitutive conception of the equals sign. *Research in Mathematics Education, 15*(1), 34-49.
Kieran, C. (2007). Learning and teaching algebra at the middle school through college levels: Building meaning for symbols and their manipulation. In F. K. Lester (Ed.), *Second handbook of research on mathematics teaching and learning* (pp. 707-762). Greenwich, CT: Information Age Publishing.
Kimmel, M., Irran, C., & Luger, M. A. (2014). Bodywork as systemic and inter-enactive competence: Participatory process management in Feldenkrais Method and Zen Shiatsu. *Frontiers in Psychology, 5.*
Kirsh, D. (2013). Embodied cognition and the magical future of interaction design. *ACM Transactions on Human–*

Computer Interaction, 20(1), 3:1-30.
Lam, W. K., Maxwell, J. P., & Masters, R. (2009). Analogy learning and the performance of motor skills under pressure. *Journal of Sport & Exercise Psychology*, *31*(3), 337-357.
Lakoff, G., & Johnson, M. L. (1980). *Metaphors we live by*. Chicago: The University of Chicago Press.
Lakoff, G., & Núñez, R. E. (2000). *Where mathematics comes from*. New York: Basic Books.
Landy, D., Brookes, D., & Smout, R. (2014). Abstract numeric relations and the visual structure of algebra. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(5), 1404-1418.
Lee, V. R. (Ed.) (2015). *Learning technologies and the body: Integration and implementation*. NYC: Routledge.
Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment: Six precepts for research on embodied learning and mixed reality. *Educational Researcher, 42*(8), 445-452.
Masters, R. S. W. (2000). Theoretical aspects of implicit learning in sport. *Int. J. of Sport Psych., 31*, 530-541.
Merleau-Ponty, M. (1945/2005). *Phenomenology of perception* (C. Smith, Trans.). New York: Routledge.
Miller, N. C., & Williams, R. F. (2010, September). *Building a better oarsman: Conceptual integration and motor learning in rowing instruction*. Paper presented at the 10th conference on Conceptual Structure, Discourse, and Language, University of California, San Diego, Sept 16-19, 2010.
Nathan, M. J., Alibali, M. W., Nemirovsky, R., Walkington, C., & Hall, R. (2015). Embodied mathematical imagination and cognition (EMIC). In T. G. Bartell, K. N. Bieda, R. T. Putnam, K. Bradfield, & H. Dominguez (Eds.), *Proc. of the 37th annual meeting of the N.-American Chapter of the Int. Group for the Psych of Math. Ed. (PME-NA)* (Vol. 13, pp. 1352-1359). East Lansing, MI: Michigan State U.
Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 341-361). Amsterdam: Martinus Nijhoff Publishers.
Newell, K. M. (1996). Change in movement and skill: Learning, retention, and transfer. In M. L. Latash & M. T. Turvey (Eds.), *Dexterity and its development* (pp. 393-429). Mahwah, NJ: LEA.
Núñez, R. E., Edwards, L. D., & Matos, J. F. (1999). Embodied cognition as grounding for situatedness and context in mathematics education. *Educational Studies in Mathematics, 39*(1), 45-65.
Piaget, J. (1968). *Genetic epistemology* (E. Duckworth, Trans.). New York: Columbia University Press.
Presmeg, N. C. (2006). Research on visualization in learning and teaching mathematics: Emergence from psychology. In A. Gutiérrez & P. Boero (Eds.), *Handbook of research on the psychology of mathematics education: Past, present, and future* (pp. 205-235). Rotterdam: Sense Publishers.
Ortony, A. (Ed.) (1993). *Metaphor and thought (2nd ed.)*. Cambridge, UK: Cambridge University Press.
Reed, E. S., & Bril, B. (1996). The primacy of action in development. In M. L. Latash & M. T. Turvey (Eds.), *Dexterity and its development* (pp. 431-451). Mahwah, NJ: Lawrence Erlbaum Associates.
Overton, W. F. (2012, May). *Relationism and relational developmental systems: A paradigm for the emergent, epigenetic, embodied, enacted, extended, embedded, encultured, mind.* Paper presented at "Rethinking Cognitive Development," the 42nd annual meeting of the Jean Piaget Society, Vancouver.
Renshaw, I., Chow, J. Y., Davids, K., & Hammond, J. (2010). A constraints-led perspective to understanding skill acquisition and game play. *Physical Education & Sport Pedagogy, 15*(2), 117-137.
Rietveld, E., & Kiverstein, J. (2014). A rich landscape of affordances. *Ecological Psychology, 26*(4), 325-352.
Roth, W.-M. (2015). Excess of graphical thinking. *For the Learning of Mathematics, 35*(1), 2-7.
Sánchez-García, R., & González, A. (2014). Las cadenas hápticas como herramienta didáctica para la enseñanza de habilidades motrices (Haptic chains as didactic tool for the teaching of motor skills). *Retos*, 26, 138-142.
Sfard, A. (1994). Reification as the birth of metaphor. *For the Learning of Mathematics, 14*(1), 44-55.
Smyth, C. (2012). *The contribution of Feldenkrais method to mind-body medicine* (Master's thesis). (UMI No. 1536829). (Saybrook University Library: ProQuest Dissertations and Theses database.)
Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.
Varela, F. J., Thompson, E., & Rosch, E. (1991). *The embodied mind*. Cambridge, MA: M.I.T. Press.
Vereijken, B., & Whiting, H. T. (1990). In defence of discovery learning. *Canadian J. of Sport Sci., 15*(2), 99-106.
Vilar, L., Araújo, D., Davids, K., & Renshaw, I. (2012). The need for 'representative task design' in evaluating efficacy of skills tests in sport. *Journal of Sports Sciences, 30*(16), 1727-1730.
Wilson, A. D., & Golonka, S. (2013). Embodied cognition is not what you think it is. *Frontiers in Psychology, 4*(58), 1-13.
Worsley, M., & Blikstein, P. (2014). Using multimodal learning analytics to study learning mechanisms. In J. Stamper, Z. Pardos, M. Mavrikis, & B. M. McLaren (Eds.), *Proceedings of the 7th International Conference on Educational Data Mining* (pp. 431-432). London, UK: Institute of Education.

