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The Thinking Hand: Embodiment of Tool Use, Social Cognition and Metaphorical Thinking and Implications for Learning Design

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Introduction

In this paper we present an evolutionary and embodied account for the co-emergence of diverse skills central to our thinking and discuss implications for learning design. Our goal is to provide a connected picture for embodied cognition that spans across multiple domains of human cognition; one that goes beyond the simple formalism of embodied cognition as motor activity having some form of influence on thinking.

Embodied cognition is not a unified theory of cognition. It represents a loosely connected set of theories grounded in multiple disciplines with the common notion of a bodily grounding for cognition. Using Kiverstein and Clark's (2009) classification of embodied approaches, which distinguishes between approaches that regard embodiment either as a component of cognition (extended functionalism), or a central tenet (enactivism), the perspective presented here falls into the latter category. It is also heavily informed by Barsalou's (2008) grounded cognition theory that characterizes cognition as simulation of perceptual, motor and introspective states.

First we present a review of work on embodiment and evolution of social cognition, tool use, and metaphorical thinking. Our goal here is to provide a connected and expansive perspective for what embodiment holds for learning and cognition; one that is not confined by the simplistic reduction of embodiment as bodily activity having some form of influence on cognition. We propose that internal simulations of sensorimotor and affective states, projection of identity on external entities and perspective taking are central to social cognition, language, tool use and abstract thinking.

Relating findings from neuroscience studies to learning design and education is a challenge. In other words, while cognitive science / neuroscience studies on human cognition are certainly interesting for learning designers and educational researchers, the implications of these studies for learning design practice are often not clear. To address these concerns, and to ground the theoretical discussions in the first part of the paper, in the second part, we present some of our learning design artifacts that exemplify the approach suggested by our embodied framework. These learning design artifacts are agent-based computational models of various scientific phenomena, embedded in a sequence of inquiry activities intended for high-school classrooms. We argue that the presented agent-based modeling activities are aligned with the embodied perspective described in this paper and provide affordances for students that build on the natural ways in which they understand a novel scientific phenomenon.

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Action as the Source of Social Cognition

"all doing is knowing, and all knowing is doing"

(Maturana & Varela, 1987, p. 26)

Since the 1980s neuroscience studies have shown that primates have a specialized system for understanding the actions of other individuals - through mental simulation of the observed actor's behaviors (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). Action understanding is a crucial skill for coordination and collaborative goal-oriented behavior of a group of individuals. But going beyond action understanding, this system also allows the simulation of the mental state of another individual during social interaction.

The theory of mind question (also known as the problem of how we understand the mental states of other individuals or "mind-reading") has long been discussed in cognitive science and social psychology. There are two main theories explaining this phenomenon. According to the theory theory (TT), mind-reading is possible by theorizing about the inner states (e.g., desires, beliefs) of another individual and predicting the observable behaviors based on the assumptions about these inner states. This is akin to developing a scientific theory about an observable phenomenon based on some unobservable, theoretical, constructs. TT approaches social interaction as a disembodied, cognitive phenomenon. A second approach, simulation theory (ST), asserts that humans understand other people's mental states by imaginatively constructing and adopting their perspective. According to ST mind-reading involves simulation of the perceived conditions of another individual, and matching the inner state of the observed individual with the resonant states of the self, i.e., with familiar states; states that one can understand as "perspectives I have taken".

Existence of a cortical mechanism in the monkey brain that activates motor areas during observation of goal-directed actions in others suggests that skills like action understanding, imitation and mind-reading involve a sensorimotor simulation system. Accumulating evidence for a similar mechanism in the human brain (Grezes, Armony, Rowe, & Passingham, 2003; Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010), now called the Mirror Neuron System (MNS), further implies such a system. This sensorimotor simulation system allows us to simulate the motor behavior and internal states of an observed individual to make sense of social situations (Gallese & Goldman, 1998).

MNS and its implications in social cognition inspired researchers to provide embodied accounts for human communicative behavior, incorporating an evolutionary perspective (see Arbib, 2002; Fogassi & Ferrari, 2007; Gentilucci & Corballis, 2006; Rizzolatti & Arbib, 1998). These accounts trace humans' unmatched verbal skills to simple skills such as grasping, action understanding and imitation, providing an evolutionary continuity for language development from early primates to humans. These theories share the core idea that a MNS for motor behavior, especially for hand movements and facial gestures, is the antecedent of verbal communicative behavior in humans. The proposed evolutionary trajectory involves, first the development of a mirror system that matches observation and execution of hand movements for action understanding, then emergence of the ability for imitation, followed by a manual (or gesture) based communication system, and the development of the vocal system, ultimately leading to complex human languages.

The evolutionary move from the ability to imitate to gesture-based

communication has made it possible for humans to express intentions by engaging in symbolic actions. For example, pretending to throw a spear to invite someone to go hunting requires a first level of abstraction where the action represents a communicative meaning instead of being a goal-directed hunting behavior.

This type of communication (and what might follow it, e.g., going hunting) requires multiple levels of (recursive) theory of mind activity. First the communicator has to execute the action expressed while simulating the mental state of the other party (e.g., my friend is in listening mode, to understand what I am trying to communicate). The listener has to simulate the action observed to interpret its meaning, which constitutes a first level of mental simulation, based on the assumption that the performing party intends to be communicative, which is the second level of mental simulation. Understanding the meaning of the action observed, and if it is executed for a communicative purpose requires evaluation of both the environmental cues (e.g., time of the day, location), and historical and cultural background (past history with the observed individual, culture and habits of the tribe etc.). Furthermore, because communication is a time-pressured activity, comprehension has to happen in a situational continuity, which makes it possible to predict, for example, whether the observed action is communicative, merely based on what took place previously.

The development of the vocal system occurred to allow for associating actions (like throwing a spear) or qualities (physical and emotional or mental states) with certain sounds. Sounds made it possible to create negotiated shortcuts for overt behaviors with symbolic meanings. Once this association is gradually established within a certain group, the sound was used as an anchor point for a negotiated action. Use of the vocal system for communicative purposes allowed both a multimodal way of communication (gestures, facial expressions and vocalizations), and also the development of a complex grammar.

Socio-cultural and situated theories of cognition submit to the idea that meaning emerges from the context within a situated continuity (Lave & Wenger, 1991). History and culture shape the semantics of the lived experience (Rogoff, 2003). However, these theories do not explain, first how situatedness maps to how the brain works, and secondly the role of the body. For example social constructivist theories focus on the negotiated construction of meaning within a socio-cultural context, without explicating how these mental structures are processed in the brain, and how the bodily states shape the lived experience of now. Embodied simulations provide explanations for these across neural, behavioral (third-person account), and the phenomenological (first-person explanation) levels. At the neural level there is accumulating research about the neural pathways participating in embodied simulations (Svensson, Morse, & Ziemke, 2009), furthermore, there are theories of how embodied simulations can constitute the source for semantic content for social cognition (Gallese & Sinigaglia, 2011).

The argument that embodied simulations are the source of semantics implies that negotiated symbols (symbolic actions) within a socio-cultural context emerge from the crystallizations of social action-situations that are repeated / reused within that socio-cultural context. Language games, rituals, specialized genres etc. can be seen as action patterns and social practices that were valuable enough to encode with symbolic gestures.

Apart from proposing a theoretical shift towards approaching social cognition as embodied simulation, social embodiment has three implications for learning.

Imitation learning. Mimicry and imitation are not simple acts of copying behavior

but rather an attempt to reconstruct the lived experience of another individual for the purposes of learning and making sense of the observed behavior. Imitation is not about perceiving actions and replicating them by motor behavior, it is rather adoption of the agency of another individual within a context, to produce similar introspective states, accompanied by matching overt motor. The leap from action understanding to imitation is proposed to be one of the major steps in the evolution of language and thought. Imitation is also not unique to humans and observed in some other animals, most noticeably in chimpanzees reared by humans, at a level comparable to young humans (Whiten & Custance, 1996). The ability to simulate the mental state of another individual and re-enact the observed behaviors is arguably the most fundamental learning mechanism for humans. It is our shortest path to adopt norms and practices in a new social context, and has served for transmission of culture since early human evolution.

Although the importance of imitation in social learning was recognized early on, the processes underlying imitation were laid in a disembodied, cognitivist framework. For example Bandura (1969) proposed that imitation involved coding of the modeled stimuli into images and words for memory representation, later to be retrieved for the reproduction of the observed behavior. The traditional approaches consider imitation as a copying of behavior, motivated by reward conditions. From an embodied perspective imitative behavior is an attempt to make sense of the actions of another individual through simulation of introspective and sensorimotor states, and re-enact them. Learning is not defined as storage of a collection of disembodied images and words in memory, but a change in the neural system to allow for partial simulation of sensorimotor and introspective states active at a given instant, at a later time.

Gestures. The second implication involves rethinking the role of gestures in learning, cognition and social interaction. Gestures accompany speech across cultures, and facilitate communication. Aforementioned theories of language evolution (for example Arbib, 2005) point to a neural system originally used first for action understanding, particularly of hand movements and facial gestures, for both the antecedent manual-based communication system and complex human languages. Brain imaging and clinical studies provide further support for the idea that gesture and verbal language production and comprehension make use of a shared fronto-parietal network active in embodied simulations, the mirror neuron system. Gestures are therefore an integral part of human communicative behavior.

Additionally gestures play a non-communicative role in cognition. The role of gestures in learning is perhaps the most studied topic in regard to the bodily foundations of learning. There is now ample research about the multiple roles gestures play in human cognition and communication. For example, gesture-speech mismatches were found to indicate readiness for learning (Garber & Goldin-Meadow, 2002), and using gestures reduces cognitive load (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001) and increases retention (Cook, Mitchell, & Goldin-Meadow, 2008). These have strong implications for learning design. For example, children‘s use of finger counting during arithmetic should be viewed as a cognitive off-load mechanism, or more technically a feedback loop for embodied simulations through recursive activation of motor and visual circuits, and not an indicator of cognitive deficiency (finger counting is still not allowed in many schools around the world). Additionally teachers’ ability to make sense of students’ gestures (especially young students), can make a difference in understanding

these students' readiness for learning a particular skill.

Tool use and the Social Brain

In its limited definition tool use can be described as use of an external physical entity to enhance human manipulative capabilities. While other animals show a limited ability to use tools (e.g., use of a stick to retrieve food), humans have an unmatched ability to construct tools and use them; showing a deep understanding of their body and how it is situated in a physical environment. Two foundational and distinct systems are proposed to be functional in tool use.

The first one allows for the semantic access to the affordances of a tool based on, primarily visual but also tactile and auditory, stimuli. While the mirror neuron system represents neural circuitry that is active both during observation and execution of actions by a conspecific, another set of neurons respond to stimuli from objects. This group of neurons, namely canonical neurons, distributed in a set of parietal and premotor areas were found to discharge in monkeys both during the execution of grasping movements, as well as when the monkey sees the object in stationary form (Rizzolatti & Fadiga, 1998). In an fMRI study with human subjects a homologue canonical system was found (Chao & Martin, 2000). A network of left premotor and parietal regions were found to be active when subjects were shown pictures of tools, and were asked to either silently name them or just observe. Other conditions included presentation of animals, faces and houses, which did not trigger similar level of activation in this system, leading to the idea that canonical neurons are specialized to respond to manipulable objects. Chao and Martin (2000) proposed that our ability to identify tools might depend on the re-activation of sensory and motor experiences attributed to the object viewed. An important finding here is that the areas activated during the identification of the tools considerably overlap with premotor areas activated during another experiment where subjects were asked to imagine right hand movements (Grafton, Arbib, Fadiga, & Rizzolatti, 1996). This suggests that identification of a tool involves re-activating sensorimotor circuits characterizing the activity that would take place during the interaction with the tool. The implication here is that the semantics of objects around us emerge from our history of interactions with them. We simulate possibilities of interactions with objects when we merely see them. Our previous interactions shape our immediate perception. In this sense, identification of an object is not about retrieving physical attributes of an object category stored in the memory and comparing it to the perceived stimulus, but rather about the visual features of the object triggering a motor program that was created either during previous direct interaction with the object or observation of another individual interacting with it.

The second system is involved in the use of a tool. There are a series of clinical studies showing that the two systems for the identification and use of the tool are dissociable (patients can have disruptions with one system without affecting the other one). The terms ideational and conceptual apraxia are used to identify these conditions, the latter one referring to disruptions with identification of a tool and the former one for a disorder of learned motor skills involving tools (see Johnson-Frey, 2004 for a review). What is the evolutionary advantage of this dissociation? Being able to acquire a conceptual understanding of a tool even when no previous experience involves direct motor interaction with the tool is possibly an advantage. Furthermore, this also suggests a dissociation of the semantic system, grounded in the sensorimotor system, from a motor

skill system. This dissociation might be the necessary ground to allow execution of motor tasks while at the same time continuing conceptual processing, which could have developed as a result of the coevolution of culture and the human brain in the recent history of human evolution.

Social learning, most importantly imitation learning, likely played an important role for the dissemination of tool use across human cultures. The ability to learn how to use tools, to recognize them and to retrieve motor programs making it possible to use the tool constituted a strong selective pressure for early hominids. This yielded changes in brain size, accompanied with changes to the digestion system to accommodate a bigger brain (Leonard & Robertson, 2005). Human hands and the related sensorimotor circuits also changed to accommodate fine motor skills required for better tool use. While the story about the coevolution of different systems in hominids can go on, the point to be taken is that the human body and brain has evolved to allow tool use, to learn about how to use tools from others, and to disseminate this knowledge. Humans are inherently tied to tools. We can't run fast, jump high, and we have a weak immune system compared to other mammals. But we can make and use tools. We make sense of using tools in a social context and the embodied simulation system used during social cognition and during tool use overlap.

Metaphorical Thinking

The study of metaphors in human thinking began with study of metaphors used in language samples in cognitive linguistics. Lakoff and Johnson (1980) proposed that humans' conceptual worlds, governing their day-to-day experiences, are largely metaphorical. Here a metaphor is defined as a mapping from a familiar source domain to make sense of a novel target domain. Since many of our intuitions, knowledge and assumptions are deeply rooted in our body, corporeal experiences often constitute the source domain. However, bodily experiences take place in a socio-cultural context, and therefore are not merely physical but are coded based on cultural presuppositions.

Since language is a primary expression of our conceptual world Lakoff and Johson (1980) focused on the study of metaphors in language. This is not to say that conceptual metaphors are used only in language; their claim was that all cognition was metaphorical and language was a good place to start. Work on metaphors progressed, later to include such notions as image schemas, conceptual primitives about spatial relations (Johnson, 1987), aspect schemas, structures coding events with temporal dimension, and conceptual blends, structuring of a new domain by way of blending multiple domains (Tunner & Fauconnier, 1995).

While the study of conceptual metaphors in language samples provided some evidence for bodily groundings of cognition, the early body of work on conceptual metaphors were ironically cognitive (based on proposed cognitive structures); these theories did not explain how metaphors are processed at the neural level and there was no psycholinguistic evidence to support the claims. As previously mentioned, the embodied cognition research program emerged in multiple disciplines in the early 1980s and it took more than a decade for unified, cross-discipline, explanations to emerge. One such theory proposes that metaphorical thinking occurs by mental simulation of the actions described in the metaphor (Gibbs, 2006). Evidence for two propositions is needed to support this claim; first, sensorimotor systems are used to understand non-metaphorical language and, secondly, metaphorical use of language activates sensorimotor resources that would be

active in the understanding of the non-metaphorical meaning (e.g., grasp the concept).

There are a multitude of studies showing that understanding the actions described in a sentence recruits relevant sensorimotor resources (see Gibbs, 2006 for a review). For example, Buccino et al. (2005) showed that action-related sentences, particularly involving hands and feet, modulate relevant parts of the motor system. A simulation theory is proposed as one possible explanation for this phenomenon: "The understanding of action-related sentences implies an internal simulation of the actions expressed in the sentences, mediated by the activation of the same motor representation that is involved in their execution" (Buccino et al., 2005, p. 361).

A study with two experiments about how observing, imagining and executing actions described in a metaphor contribute to the comprehension of the metaphor provides supporting evidence for the second proposition (Gibbs, Gould, & Andric, 2006). The first experiment showed that watching, imitating, or imagining the action in an abstract metaphor improved subjects' ability to imagine what is described in the abstract metaphor. For example, watching, imitating or imagining the grasping movement before listening to the *grasp the concept* metaphor facilitated imagining the metaphorical meaning. Gibbs, Gould, and Andric (2006) explain this phenomenon by arguing that: (a) "People's understanding of metaphorical language involves their engaging in embodied simulations that in the case of expressions like 'stretch for understanding' and 'chew on the idea' make these phrases both understandable and conceptually plausible" (p. 222), and (b) "Having people watch, imitate, or imagine engaging in relevant embodied actions (e.g., chewing or grasping) may enhance the degree to which they conceptualize metaphorical actions through embodied simulations" (p. 224). In the second experiment it was shown that in two reading time tasks performing or imagining body movements appropriate to metaphorical content before reading metaphorical phrases improved participants' immediate comprehension of these phrases.

An fMRI study, where no neural congruence was found between observations of hand, foot and mouth movements and understanding metaphors with relevant actions (e.g., grasp meaning) provides conflicting evidence in regard to use of bodily simulations in understanding metaphors (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006). A difference in processing between novel and familiar metaphors is proposed as an explanation. In a novel metaphor the salient feature is the non-metaphorical meaning of the action word, and once the metaphor becomes familiar the metaphorical meaning (e.g., understanding the meaning vs. grasping) is salient, reducing reliance on the original action processing (Aziz-Zadeh & Damasio, 2008).

The Nature of Embodied Simulations

" Every act of knowing brings forth a world."

(Maturana & Varela, 1987, p. 26)

In the previous sections on social cognition, tool use and metaphorical thinking we explained how embodied simulation is a theme that connects diverse human skills and explains how cognition is grounded in bodily processing across different domains. Before focusing on the learning design implications of these ideas we would like to further discuss the nature of embodied simulations.

Is There a Homunculus?

Similar to the word *visualization*, *simulation* implies an inner self who experiences what is simulated. The classic idea of a homunculus experiencing what is simulated is problematic because it leaves out how the current experience intermingles with what is simulated, and makes the act of simulation a reenactment, rather than application of previous sensorimotor and affective states to makes sense of what is now experienced. The idea of a homunculus experiencing simulations is somehow similar to the Cartesian Theatre model (Dennett & Kinsbourne, 1992; Dennett, 1991) where the immaterial soul observes a representation of the outside world leading one to wonder whether "simulation" is the appropriate word. Nevertheless, the term "embodied simulation" is commonly used to represent theories that argue for the sharing of neural mechanisms between sensorimotor process and higher-level processes, the latter making use of partial simulations of sensorimotor processes by activating neural circuitry for bodily perception and action (Gallese & Lakoff, 2005; Svensson et al., 2009). In this sense an embodied simulation is not a reenactment of a previous experience but rather a continuous process where one constructs a sense of what is experienced "now" by mixing the sensorimotor and affective states of the present with salient ones of the past.

Reenactment vs. Recreation

To further this discussion, we focus on simulation theories (ST) of mind-reading. According to ST, people understand others' behaviors by taking on the perspective of the observed individual. In this sense mind-reading is a mimicking or replication activity where the mental life of the observed person is simulated (Gallese & Goldman, 1998). There is no homunculus watching the simulated replication of the observed behavior on a Cartesian theater. Rather, the observer replicates the behavior of the observed to have a similar experience through the simulation mechanism. The degree of closeness of this replication to the original phenomenal experience may depend on the previous experiences of the observer: Similar sensory and motor repertoires of the observer and the observed might yield to a more authentic replication. Nevertheless, mind-reading here can never be a complete replication of the authentic experience since it is a re-creation from the perspective of the observer. The qualities of this re-creation are grounded on the peculiarities of the observer's previous experiences, brain and body anatomy, history of interactions and endless other factors.

Similar to mind-reading, action understanding does not constitute an act of replication but rather re-creation. When one sees another individual performing an action, neural circuitry that represents the observed action is activated in the observer's motor areas. The observer utilizes a motor representation of the observed action (Rizzolatti, Fogassi, & Gallese, 2001). In a single neuron study conducted with monkeys, when the observer saw only a part of an object-oriented grasping movement (sight of the movement was partially hidden), activations in the premotor cortex matched the activations of observing the entire movement (Umilta et al., 2001). This motor representation is not a complete replication of the motor activation of the observed individual's brain. Similarly, the motor representation is not modality dependent. Rather, when the observer has a repertoire of relevant multimodal interactions, in a given situation a single modality can trigger activations in other modalities that are not necessarily present in the observed action. In a single neuron study with monkeys, some of the mirror neurons responding to auditory stimuli (sound of ripping a paper) were also activated with visual stimuli (only sight of ripping a paper), provided that monkeys

previously observed the same action in both modalities (sound and sight of ripping a paper). Similarly, when only auditory stimuli were presented, mirror neurons responding to only visual stimuli were activated as well (Kohler, 2002).

The act of re-creation is not only an interpretation within the boundaries of the modalities observed but with other modalities as well, even with the ones that are not a part of the observed behavior. How is this possible? Edelman (1987) defines two characteristics of multimodality: (1) Degeneracy, which means redundancy of modalities. Any single function can be carried out by more than one configuration of neural mechanisms. For example, we can encounter space through sight, movement, sound, touch, and to some extent, smell. We can understand space even when we lack one or more modalities. Blind children still have spatial concepts grounded in different clusters of modalities (Landau & Gleitman, 1985), (2) Reentry, is the explicit interrelating of multiple simultaneous representations across multiple modalities. For example, one's experience with a cup of coffee is not only visual but also involves smells, physical properties of the cup, such as the texture and temperature, motor movements for moving the cup and drinking it, and finally the taste of it. All experiences related to a cup of coffee with different modalities are time locked. Multiple maps are formed between the physical properties of the cup of coffee during the experience: One map between physical properties and the visual system, a second map between physical properties and the haptic system, and a third map between the smell and the olfactory system. At the same time reentrant maps among the visual, haptic, and olfactory system are formed. These independent mappings of the experience become interrelated in real time, thus educating one another, ultimately allowing the system to recognize higher-order regularities that transcend particular modalities (Smith & Gasser, 2005). For example, in Kohler's (2002) study, reentry map between the auditory and visual systems allowed the monkey to "recreate" the sight of ripping a paper when only the sound of ripping was presented with the stimulus.

Connecting Embodied Cognition with Learning Design

While the research elucidating the connections between the brain, body, and world and how these systems co-evolved is certainly interesting, how this work informs the design of learning environments is an open question. In fact connecting theoretical and empirical work on human cognition and educational design has been identified as a major goal for a new field of study commonly referred to as educational neuroscience, neuroeducation, or mind, brain and education (Fischer, Goswami, & Geake, 2010; Varma, McCandliss, & Schwartz, 2008).

In this section we present a brief review of current perspectives on the implications of embodied cognition for education and propose a new perspective, which we argue is lacking in the current literature. We ground our discussions by presenting some learning design artifacts we have developed that exemplify our approach.

Embodied Learning & Design

While the origins of the embodied cognition research program can be traced back to late 1970s, the diffusion of work on embodiment in psychology, linguistics, philosophy and artificial intelligence to education and learning design took two decades. The slow movement of new ideas in psychology and the cognitive sciences to educational research and practice was at least partially responsible for this delay (a trend that was also

observed with the cognitive revolution of 1950s), though the entrenchment of the cognitivist perspectives in educational theory further impeded the diffusion of research on embodiment. However, those that viewed learning as a constructivist process, rooted in a social and cultural context, had relative ease in understanding work on embodied cognition. For this reason, we view situated theories of cognition and learning theories that emphasize the contextual nature of learning, and highlight the importance and utility of personal idiosyncrasies in the learning process (Brown, Collins, Duguid, & Seely, 1989) as the first entry points for how ideas of embodiment can be infused into educational theory.

We see two problems with current work on embodied cognition and learning design. The first is the overemphasis on physical activity. While we agree that the use of physical activity to impact conceptual processing is an obvious implication of embodied cognition research; not every learning activity that involves physical activity can be regarded as "embodied." Secondly, the phrase "embodied learning" implies that there is learning that is not embodied (would that be "disembodied" learning?). While this is certainly "tongue-in-cheek" this particular phrasing seems to be based on a belief that bodily mechanisms simply augment conceptual processing, providing a larger "benefit" for some activities or conditions than others. This perspective leads to "embodied design" aims to activate an embodied form of learning, suggesting that learning would not be embodied otherwise. We argue that cognition is embodied regardless of the learning activity. What we strive for, as educational designers, is to design learning environments that are compatible with what we know about how learning happens. In this sense, "embodied design" is not design that activates embodied learning; it is design that resonates with the way we learn, which is always-already embodied.

Embodiment Simulations, Perspective Taking & Learning

We argue that one of the core mechanisms of the embodied mind is our ability to activate sensorimotor states that are not part of our immediate perceptions or actions (no external stimuli, no overt action). This allows for a wide range of skills, including understanding and imitating actions of others; having an immediate sense of the affordances of objects around us by way of simulating interactions with them; and engaging in verbal communication. We propose *perspective taking* as a construct that connects these diverse skills. Here, perspective taking refers not only to our ability to assume the perspective of another individual, but also to assume the perspective of non-human or even inanimate entities to predict their behaviors and potential ways of interacting with them.

Our natural tendencies for perspective taking in understanding new domains have been previously harnessed by constructionist approaches to learning and design (Papert & Harel, 1991; Papert, 1980). For example, in the LOGO programming language users are encouraged to draw shapes and objects using a digital Turtle. Specifically, users are encouraged to "Play Turtle," that is, to "think like the Turtle," or to take on the perspective of the Turtle by projecting themselves onto the Turtle. Papert (1980) describes this activity as *body syntonic* (allows use of knowledge and awareness about one's body) because one can use knowledge of movement in real physical space to draw shapes with the Turtle.

Embodied Modeling: Perspective Taking and Learning about Complexity

Wilensky and Reisman (2006) proposed an embodied modeling approach using NetLogo (Wilensky, 1999), an agent-based modeling tool, to provide learners opportunities to build models of various phenomena such as predator-prey population relations or the synchronized flashing of fireflies. The embodied modeling approach described is essentially an agent-based approach to modeling, in which rules of interaction among different elements are described at the individual level as opposed to the aggregate level. However, what makes this approach embodied is that it gives learners the opportunity to put themselves in the place of an agent and develop rules describing the behaviors of the agent, only then to run the model and observe the complex patterns that emerge from the interaction of many agents.

The general goal of the agent-based modeling approach is to help learners construct a decentralized and probabilistic understanding of the complex phenomena exhibited by a system encompassing multiple levels. The authors propose that providing opportunities to learners to take perspectives of agents in the phenomenon studied, while at the same time observing aggregate level changes, is effective for two reasons. First, the embodied modeling approach offers feedback to learners at the individual and the aggregate level. And second, learners are better able to understand the rules at the individual level (as opposed to an aggregate formula) because "students will often try to make sense of a given rule set by assuming the perspective of the individuals within the model and using their imaginations" (Wilensky & Reisman, 2006, p. 186). Beyond helping with spotting errors, simulating the agency of an agent is proposed as a powerful aspect of the embodied modeling approach: "When their knowledge of the individual biological elements is combined with their knowledge of their own embodiment, their own point of view, they are enabled to think like a wolf, a sheep, or a firefly" (p. 203). It should be noted that while the main focus of this article is on simulations with NetLogo, the use of perspective taking to understand complex phenomena is not confined to computational modeling environments. A similar approach to understanding complex systems by playing the role of an individual (e.g., ant) in a series of activities in a non-computational environment was proposed as well (Resnick & Wilensky, 1998).

One form of agent-based modeling, *participatory simulations*, particularly harnesses the perspective taking aspect of the modeling activity (Wilensky & Stroup, 2002). In a participatory simulation students participate in the modeled ecology as one of the agents. For example in participatory simulation modeling the predator-prey relations in an ecosystem, each student controls either a predator (e.g., wolf) or prey (e.g., sheep).

Why is it advantageous to assume the role of an agent situated in a system (agent-based thinking) in our attempts to understand a complex phenomenon? How does it tap into the way our minds work? First, agent-based thinking is a theory of mind activity where the learner imagines how it would be to be, for example, a firefly. As was discussed earlier, embodied simulation of the sensorimotor and introspective (e.g., intentional and emotional) states, either of another individual or the self, is a central mechanism in human cognition. In this sense, adopting an agent-based perspective resonates with the usual way we make sense of our world.

Perspective taking in an agent-based environment also involves imagining how the agents in a system might perceive the affordances of other objects within the ecology of the system. That is, the agent-based perspective involves developing a sense of the affordances of other objects in the system, from the eyes of an individual agent.

Therefore, the projection of agency onto a sheep in an agent-based model also involves seeing the microworld from the eyes of the sheep.

Considerable work has been done on the use of agent-based modeling in learning about and understanding complexity in various domains (for example Blikstein & Wilensky, 2007; Sengupta & Wilensky, 2009; Wilensky & Resnick, 1999). To ground our discussions to this point and to further the previous work done using agent-based modeling in STEM education, we present a series of educational designs that are heavily informed by the presented embodied approaches. These design artifacts include agent-based computational models as well as virtual models coupled with physical computational tools. Each of these artifacts is embedded in a carefully constructed sequence of science inquiry activities meant to encourage students to connect prior experiences in the physical world to complex abstract phenomena. The artifacts presented here were developed as part of the ModelSim (Enabling Modeling and Simulation-Based Science in the Classroom) project (NSF# DRL-102010).

Learning Design Artifacts: Science Inquiry with Agent-Based Modeling

In this section we present four design innovations; each of them offering an alternate method of encouraging learners to connect agent (micro) and aggregate (macro) level phenomena associated with the Particulate Nature of Matter (PNoM). The central theme here is that students are given opportunities to take perspectives of and have direct perceptuo-motor experiences with elements at both the agent and aggregate levels, leading to an *embodied understanding* of the domain studied, which is characterized by the ability to project one's identity into elements of a system at different levels to ground a holistic understanding (see Brady et al., in-press for more detailed description of these activities and the underlying design approach).

Modeling the Diffusion of an Odor: Being the Sensor

This activity serves as the introduction to the PNoM unit and engages with the phenomenon of the diffusion of an odor throughout a room. In the first stage of the activity, the classroom group as a whole acts as a distributed "smell-sensor" array, collecting data on their perception of smell intensity over time, as an odor is released into the room. Each student enters her individual, location-specific readings of smell intensity, and these individual data are aggregated to create a shared data set. A visualization of this data set provides evidence to fuel whole-class discussion of how the smell spread through the room, and what mechanisms might account for patterns observed in this spreading phenomenon. In the second stage of the activity, students work in small groups to construct a runnable agent-based model of one aspect of the shared diffusion experience that they have chosen to explore. For instance, one group might attempt to reproduce and explain the general pattern of spread; another might investigate possible reasons for fluctuations observed in different sensors' readings over time; and a third might inquire into the effects of temperature on aspects of the diffusion phenomena such as the rate of spread. As the different groups develop their models, they post their works-in-progress to a shared "gallery," which enables them to monitor, reflect on, and comment on each other's work in real time.

Both stages of this activity allow students to acquire a novel experience by projecting themselves as a component of the system being explored. Acting as a sensor raises questions about how a sensor works, which in return leads to questions about the

nature of what is being sensed; the gas particles. In the second stage students build a model of the diffusion experience that they participated in. In this stage learners explore and hypothesize about how particle-level dynamics might lead to the outcomes observed by switching between the perspective of a particle and the aggregate-level outcomes observed. The key innovation here is the sensory experience of smelling the scent, assessing its intensity, and recording its strength, which together constituting the functioning of a sensor, connects the sensory aggregate level experience with the particle-level representation of the phenomenon. This sensory experience is again accessed as students are given the opportunity to project their identity to different components of the system in an iterative cycle of perspective taking, switching perspective to look at the entire system (both at the aggregate/experiential and particle levels), and switching back to the agent-based perspective. Inferences about the diffusion of particles based on sensor-readings in the model are grounded in an intuitive and self-referential understanding of how a sensor works. The sensor is a component that exists at both stages of the activity (scent diffusion experiment & modeling) and acts as a *phenomenological connector* between the two levels (aggregate & particle-level). Acting as the sensor gives direct access to an understanding of what the affordances of a sensor are. The bodily experience of acting as a sensor also grounds conceptual ideas about how a sensor functions and how particles behave during their interaction with a sensor, which then is generalized to how gas particles behave during diffusion.

Bifocal Activities: Bridging between Physical and Virtual Worlds

Bifocal activities attempt to "merge robotics/sensing and multi-agent computer simulation" (Blikstein & Wilensky, 2007). This is accomplished by pairing the interactions with a virtual computational model to physical experiences with the modeled phenomenon. In a bifocal activity, explorations in the "real world" facilitate interpretation, exploration, and construction in the virtual space.

In one particular PNoM activity, learners are provided with a physical syringe and a force sensor, which is in turn connected with the virtual representation of the plunger of the syringe (Fig. 1). When the student presses the physical syringe down upon the pressure sensor, as one would expect, the physical plunger is depressed, reducing the volume inside of the syringe. However, because the pressure sensor data is utilized in the virtual computational model, this action in the physical world also causes a virtual plunger in the model to move proportionate to the amount of the pressure applied. As learners continue to press on the plunger (at varying levels of pressure), they see how both the physical and virtual plunger in the model moves, and how the change in the volume of the barrel affects the gas particles observable in the model. In this way the virtual model makes visible mechanisms that underlie phenomena interacted with directly in the physical world.

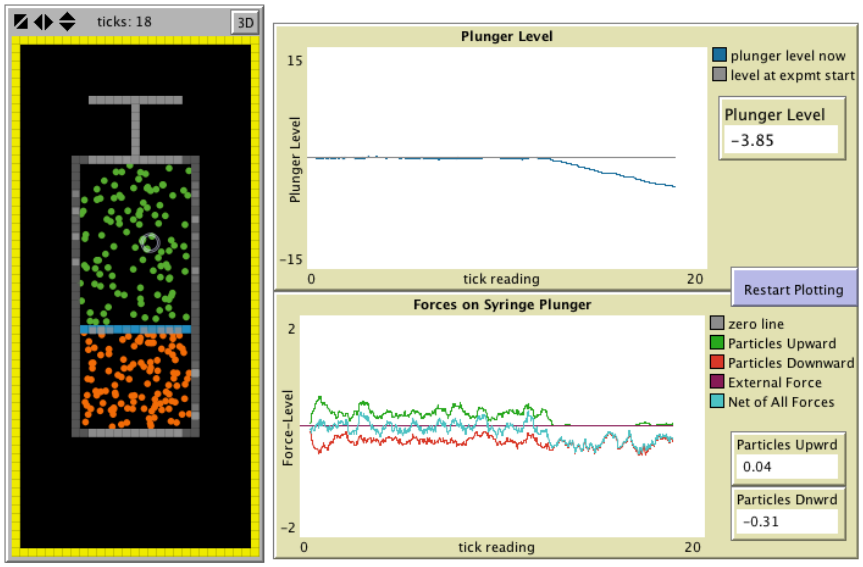

Figure 1. The virtual syringe model, connected to a physical syringe through a pressure sensor.

This particular bifocal activity provides an opportunity to develop reentrant maps (Edelman, 1987, 2004) between the motor program of pushing the plunger and the visual images of particles being compressed as a result of the plunger movement. This reentrant map informs the affordance of the plunger representation in the model. The act of pushing the plunger and the reactive force meeting it provides a sensory feedback about the outcomes of the collective behavior of the gas particles in the barrel, while the observation of the particles in the barrel being compressed provides a visual feedback. This provides a unique experience for the students since they both control one component that introduces a change to the system, but at the same time project their identity on the gas particles to get a sense of how this force changes the behavior of the particles, and their aggregate results.

In a second bifocal activity, groups of students engage in an engineering task that also blends the virtual and the physical. Here, learners build a virtual piston and a program for driving it, using their understanding of the relations between temperature, pressure, and volume. They then use this virtual piston to drive a physical machine that they have also created, to accomplish a pre-determined mechanical goal. This activity inverts the casual relation utilized in prior activities between the physical and virtual setups. This time changes in a virtual computational model drive the movements of a physical apparatus. This encourages learners to explore how the collective behavior of many small gas-particles can cause interesting and useful changes on an observable scale. During this activity learners again engage in an iterative cycle of making predictions about the affordances of both the physical and virtual tools provided for manipulations at the aggregate and agent levels, and modify these based on their interactions. Once again learners engage in a cycle of perspective shifting from gas-particles, to components of the physical setup.

Emergent System Sandbox (ESS)

An emergent system sandbox model provides students with ample opportunities to act as different components of the system in an open-ended, manipulable environment.

The interactions in a sandbox model are goal oriented in the sense that the students would either be conducting an investigation to test their theories or designing an artifact that shows a certain type of outcome. Sandbox models are open ended in way students can manipulate the state of the model by using various tools, which can change the distribution, quantity and behavior of the particles in the model. This requires students to figure out the affordances of each tool

Event Programming

A final innovation that we have pursued in the ModelSim project to ensure compatibility with what we know about embodied learning is the inclusion of "event programming" in the design of computational models. When learners create virtual computational models they are often limited in how they can initiate new actions in the model. Typically, all actions are "set in motion" at the onset of a computational model—the initial conditions are defined and the model is set to run and respond to these conditions automatically over time. Any attempt to introduce new conditions into the system must be caused by the user manually: often by activating preprogrammed instructions that causes the change or by stopping the model, making changes, and then restarting the model. By allowing learners to program timed events into a system, we encourage learners to not only simulate how a complex system may play out, but to also conceptualize the summative effects of each action.

The particular model where event programming is utilized once again involves the movement of a piston due to the interactions and behaviors of gas particles. Before beginning this activity, learners have explored only closed systems. Because the number of particles remains constant in a closed system, learners have become accustomed to moving the virtual plunger (changing the volume of a chamber) solely by increasing or decreasing the temperature of regions within the system. Before beginning this final activity, learners interact with a physical demonstration of a complex piston system that includes valves—allowing for the addition or subtraction of gas particles into the system. Two to four students at a time volunteer to interact with this physical system and work to coordinate their actions with the two plungers and two valves in an effort to maximize the number of full piston cycles per minute.

After working with the physical apparatus, students once again are confronted with a virtual computational model. While this model looks similar to the previous models—allowing for customized placement of gas particles and walls and the inclusion of a movable "plunger"—this model also allows learners to add six key event-types: the addition of particles to the top chamber or bottom chamber and the opening or closing of walls in the top and bottom chamber (Fig. 2). A timeline is provided, on which events can be introduced and arranged through mouse-based interactions. Instances of any even-type can be placed at any point on the timeline as many times as the user chooses (though if a wall is "closed" it must be "opened" before it can be "closed" again). On executing the event-program, a moving "time cursor" passes over the program indicating the present moment and firing the corresponding events in the virtual model. This new version of the piston model allows learners to explore the implications of an open system for mobilizing gas particles to achieve useful emergent phenomena.

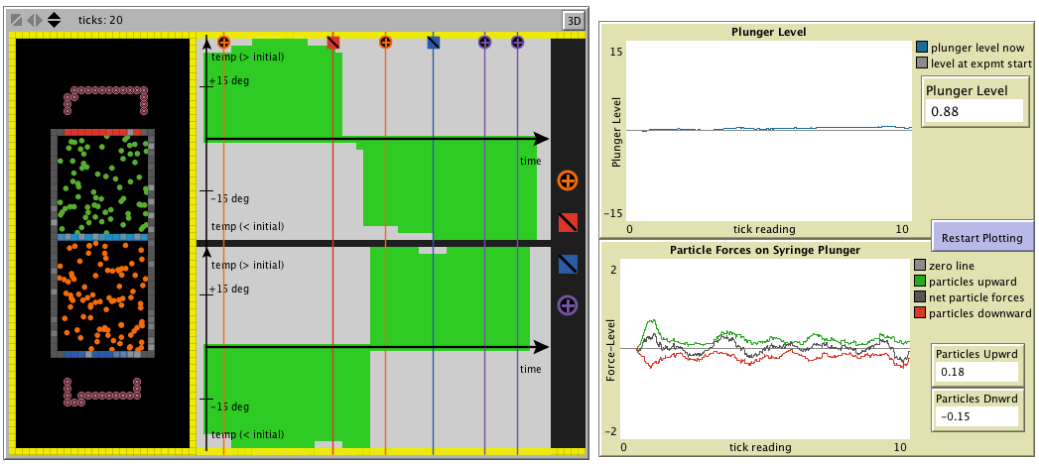

Figure 2. The event programming interface.

Of particular note to this paper is the importance of allowing learners to first experience an "open system" in a physical apparatus before exploring such a system in a virtual model. Here the value is not "physical activity" but the ability to use the perspective of action, gained through the exploration of the physical model, to conceptualize the behaviors observed and actions enacted in the virtual space. While using the computational model, learners reinterpret the forms and entities found in the model based on their physical experiences with the demonstration "tool." Likewise, learners reinterpret what they have observed using the physical apparatus based on their observations of the affect virtual gas particles have on the virtual syringe plunger. Finally, because each programmed event exists on the same timeline, learners must simulate "to the end" how each event cumulatively impacts events that follow leading to a complex cycle of simulations and inferences that continually build upon one another.

Conclusion

A Cartesian mind-body duality has long been engrained in the study of learning and cognition. Embodied cognition is a research program that has stemmed from independent efforts in multiple disciplines, aiming to reconcile human experience of corporeal and intellectual existence. Recent research on evolution of cognition and the brain has provided us with a new perspective on how uniquely human cognitive skills have evolved through redeployment of mechanisms that initially evolved for other bodily skills. Here we first presented an evolutionary approach to embodied cognition that connects diverse human cognitive skills, both evolutionarily and mechanistically and goes beyond the limited formulation of embodiment as physical activity having some sort of effect on thinking. We argued that the ability to simulate sensorimotor and affective states based on previous first-hand and perceived experiences enables us to look at the world from the perspective of other entities, both human and non-human, animate and inanimate. This embodied simulation and perspective-taking ability enables unprecedented social and cognitive skills, like language, complex social cognition, tool use and conceptual thinking based on metaphorical relations among experiences in different domains.

Next, we discussed the implications of research and theoretical perspectives presented for learning design. Prior efforts to relate embodiment to learning design have mostly focused on exploring how physical activity can enhance learning outcomes. We

argued that the relation between bodily processes and learning should be discussed outside of the limited frame of improving learning outcomes, and rather as part of an effort to redefine learning and cognition. Model-based science inquiry units were presented as case studies to discuss the learning design implications of our approach to embodiment. We proposed two theoretical structures to reframe the relation between embodiment and learning design; The first one, *perspective taking*, refers to our core ability to project our identity to external entities by use of embodied simulations. We argued that understanding a novel system involves taking the perspective of different components of the system at different levels (e.g., for gases, aggregate level gas behavior and the behavior of gas particles at the microscopic level). We exemplified how a learning program can provide immersive opportunities for perspective taking within the ecology of the system studied. The second construct is called a *phenomenological connector*, which is bodily experience that provides first-hand experience into how a component functions at different levels of a system. We presented four example activities that involve perspective taking at multiple levels and where students acquire experiences that can act as phenomenological connectors. Particle level phenomena are often abstract and hard to understand for students. These activities provide students with opportunities to acquire multi-modal experiences, which then enable them to participate imaginatively in the system as a component, both at the aggregate and microscopic-levels. The first one involves acting as a tool (i.e., a sensor) in a physical scent diffusion experiment and modeling diffusion at the particle level. The second one allows learners to manipulate the functioning of a system with a physical tool (i.e., the syringe), while observing the effects at the particle-level. This resembles use of a microscope, with the additional functionality of manipulating what is happening at the microscopic level. In the third activity students develop a model that drives a physical setup, reversing the relation between the virtual and physical worlds. This activity allows simultaneous perspective taking at both the particle and aggregate levels.

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