A feeling of knowing:
Towards an embodied contemplative pedagogy for learning

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A thesis submitted in partial satisfaction of the
requirements for the degree of

Master of Arts

in
Education

in the
Graduate Division

of the
University of California, Berkeley

Committee in charge:
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Spring 2023

"I know that nothing has ever been real
without my beholding it.
All becoming has needed me.
My looking ripens things
and they come toward me, to meet and be met"
(Rilke, 2005, p. 43)

"Within all human activities, it is urgent to create, between the stitches of the tightly-woven fabric of rules, constraints and strained schedules that inhibit this contact, joyful spaces of resistance: spaces where, together, we allow ourselves to slow down, to breathe, to listen to the felt dimension that animates our lives, to let new visions and new stories emerge from it, to imagine new ways of doing things, demonstrating here and now that they are possible."
(Petitmengin, 2021, p. 179)

Abstract

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Drawing on enactivist theory, material-engagement theory, and contemplative phenomenological approaches, this research explores the relationship between expressive media and semiotic systems in conceptual learning, emphasizing the importance of attending to the felt dimension of experience. The study explores clay as a medium for eliciting participants' tacitly multimodal phenomenology of visually observing scenarios of acceleration, highlighting the potential of expressive media to afford rich sensory engagement and support students in grounding conceptual understanding in their perceptual phenomenology. This research invites us to consider the pedagogical implications of selecting semiotic media, pointing towards a new paradigm for action-based embodied design of learning environments that emphasizes the multimodal nature of conceptual sense-making. By departing from an *a priori* preference of any particular sensory modality, semiotic medium, or representational form and, instead, fostering idiosyncratic divergent expression of tacit perceptual phenomenology, the proposed pedagogical approach could foster a classroom epistemic climate of inclusivity, curiosity, and epistemological pluralism.

Introduction

Take a moment to pause. Wherever you are, feel your feet on the ground, and your body as weight. Look up from these words for a moment. What draws your attention? Rest your attention on that which called you, just for a brief period. Perhaps a tree outside the window, or a pen whose body has caught the light and glints golden on the desk. Invite that Other in. Notice a natural curiosity that may arise. A felt sense of being drawn into relationship with this Other. What might it mean to dialogue with this entity? What language does pen know, do leaves speak? What shifts, what whispers, what touches and what is being touched?

Now, if you agree, imagine yourself sitting at your gate at SFO. You arrived early and security was a breeze. You have time to wait before your flight, and you have a clear view of the runway from your seat. You watch, transfixed, as an airplane rolls down the runway, slowly gaining speed for its takeoff velocity. The roar of the engine fills the air, and billowing heat spirals from the turbines. Though you yourself are motionless, you are a participatory observer, perceiving the acceleration of the plane in relation to your own stillness. Notice, within you, the movement of the plane, reflected internally. Perhaps an inner pressure, an intensification, an expanding, a stretching, or a pulling. How would you describe that feeling to a friend? As a gesture? As a sound? A taste?

Seated in classrooms, students taught to model acceleration are expected to use mathematical symbols to describe this kinematic phenomenon. When asked to "show one's work," what is given are pencil and paper, a tablet, or perhaps a keyboard: tools whose strengths lie in symbolic representation. One's thought process is to be shown via mathematical symbols, intended to detail the steps that have led up to a solution. But is that, indeed, the whole picture of the mental effort leading from the phenomenon to its symbolic articulation? The semiotic machinery of algebraic symbols does not afford expressing the fluid, morphing nature of mathematical thinking (Lemke, 2003). Explorations, stumblings, and intuitions are difficult to convey in this way and are often lost. Gesture and mental grasping, such as metaphor, making up so much of our sense-making, are elided in exclusive favor of formal symbolism (Young, 2021). Thus, an untapped richness, rooted in the felt dimension of experience and emerging as synaesthetic participation, remains unprivileged in education. Even as this multimodal, pre-conceptual substance is critical within the problem-solving process, it is commonly overlooked in educational practice (Petitmengin, 2007).

Common lessons on kinematic phenomena conventionally involve formula-first, out-of-hand learning, in which students learn formal equations and then apply them to various described scenarios (cf. Nathan, 2012). A more hands-on approach may involve using manipulatives to model acceleration, such as having students take quantitative measurements of a miniature car rolling down a ramp (e.g, Lindwall & Lymer, 2008). However, these approaches offer little in the way of supporting students in establishing a relationship to their felt experience of acceleration. Disconnected from the sensuous, lived experience, such teaching approaches pay little heed to naïve understanding, metaphorizing, or other phenomenological substance unfolding within the student.

I conjecture that such formalism-first or quantitatively focused teaching approaches in education neglect students' multimodal, pre-conceptual processes of meaning-meaning to the

detriment of a deeper, richer understanding of the subject matter at hand. In denying opportunity for such multimodal exploration and expressivity, the thread connecting symbolic representation and embodied understanding is severed. As neuro-phenomenologist Claire Petitmengin challenges:

> Are our teaching methods well adapted? [...] The intention is to fix a meaning, not to initiate a movement. Which teaching methods, instead of transmitting contents, could elicit the gestures which allow access to the source experience that gives these contents coherence and meaning? (Petitmengin, 2007, p. xxx).

This research effort explores the multimodal[1] concerting of our sensory experience shaping the many dimensions of our meaning-making and, by extension, our ability to learn. It is from this richly sensuous and participatory source dimension, I submit, that idiosyncratic symbolic representation emerges and can become formalized, while maintaining a thread of connection to one's felt experience. In this way, I further conjecture, one's learning remains rooted deeply in one's lived experience, even when extended to abstract and symbolic representation. When supported in both attending to, and expressing, the gestalt of one's perceptual phenomenological experience across sensory modalities, learning may become more firmly rooted in direct perception, a feeling-as-knowing that maintains a richness of coherence and meaning.

Radford's semiotic-cultural theory recognizes the affordances of media to act as semiotic means of objectifying pre-conceptual notions of understanding throughout the learning process (Radford, 2003). As Abrahamson (2009) puts forth, "students' expressivity may be either facilitated or limited by the adequacy of available media to encode emerging images they wish to communicate" (p. 34). Furthermore, as Malafouris (2020) maintains, in expounding his material-engagement theory, "New artifacts create novel relations and understandings of the world. New materialities bring about new modes of acting and thinking" (p. 4). Malafouris describes this paradigm as "thinking as 'thinging'" and uses the relationship between potter and clay as a case study to demonstrate the intertwined perception-shaping relationship between maker and material. He asks, "Where does the thinking of the potter end and the forming of clay begin? Where do we draw the lines that supposedly separate thoughts, feelings, perceptions, and actions?" (p. 5). I suggest that we look at this same relationship, but between student and expressive material provided in the classroom. Where does the thinking of the student end and the engagement with material begin?

As such, expressive material made available to students play a critical role in the process of objectifying pre-conceptual notions of understanding. Therefore, education designers must examine the adequacy of media to support students in expressing their intuitive grasping of content—the substance of pre-conceptual notions of understanding—and enacting it in shape and form. As Morgan and Abrahamson (2018) describe, work must be done to resolve the "'epistemic bottleneck' between pre-symbolic notions and articulated expression" (p. 110). The driving design problem thus is twofold: that the phenomenology of intuitive grasping is underexplored in the learning sciences, and therefore, available media do not afford a feeling-as-knowing grounded in sensory experience.

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[1] See Appendix A for definition of commonly used terms

The aim of this research, therefore, is to operationalize understanding of the unfolding process from felt experience to conceptual formation, in service of more holistic, inclusive, and accessible pedagogical approaches for mathematics learning. What would it mean to learn from a place closer to the heart of our experience? Might we reclaim vital aspects of our being-in-the-world that have been underemphasized or lost entirely, "recalling us to our participation in the here-and-now, rejuvenating our sense of wonder at the fathomless things, events and powers that surround us on every hand?" (Abram, 1996).

Epistemological orientation

As a researcher, I identify as a critical constructivist, first

> disengag[ing] from the natural attitude and focus[ing] instead on [it] in order to reflect upon it…. then, from this reflective perspective, describ[ing] all the particular intentionalities….of the natural attitude in order to understand the world and our place in it. (Burkhart, 2004, p. 21)

In this way, the focus of my research orients towards radical empiricism, "examining experience as a whole with greater care and seeing the interrelationships of its ingredients" (Cobb, 2012, p. 4). I am particularly interested in the ways in which "feelings, beliefs, sensory experiences, memories, anticipations, bodily experience, and intellectual activity are all equally real and very much bound up together" (ibid, p. 5) in our learning processes. I believe that in fore-fronting these more "radical" dimensions of learning, the culture of education may begin to shift towards one that "may yet reintegrate the sacred with the secular in ways that promote freedom and self-determination" (Guba & Lincoln, 2005, p. 128). This occurs as we become more intimate with our own lived experience and the roots of our meaning-making, while cultivating the ability to call upon this dimension of our being as a resource for authenticity, creativity, purpose, innovation, and belonging. To this end, I draw from my extensive background in contemplative practice, particularly insight meditation rooted in Mahayana Buddhism and imaginal techniques rooted in Vajrayana Buddhism and Tantric Shaivism. May this research contribute to a deepening of both our understanding and emancipation in relation to our human condition.

Theoretical orientation and conceptual framework

The focus of this research is the realm of subjective experience antecedent to the synthetic bifurcation of cognition and affect—knowing and feeling—so rife in cognitive science discourse. This realm of subjectivity, emerging via sensuous participation with the world, consists of the primordial qualia from which one's meaning-making kaleidoscopically coagulates into concept and symbol: what Merleau-Ponty refers to as "*la chair du monde*" [the flesh of the world] (Merleau-Ponty, 1964, p. 116). This realm is underexplored within the context of education. My own research project utilizes the lenses of enactivism, contemplative-somatic learning, ecological dynamics, material-engagement theory, and phenomenology to explore the multimodal somatosensory qualities of this feeling-as-knowing in relationship to the affordances of the environment and media present during learning. In the following sections, I will first provide a brief overview of each theory and its implications for tackling the general design problem addressed by this project, and then I will outline a cohesive structure of these theories

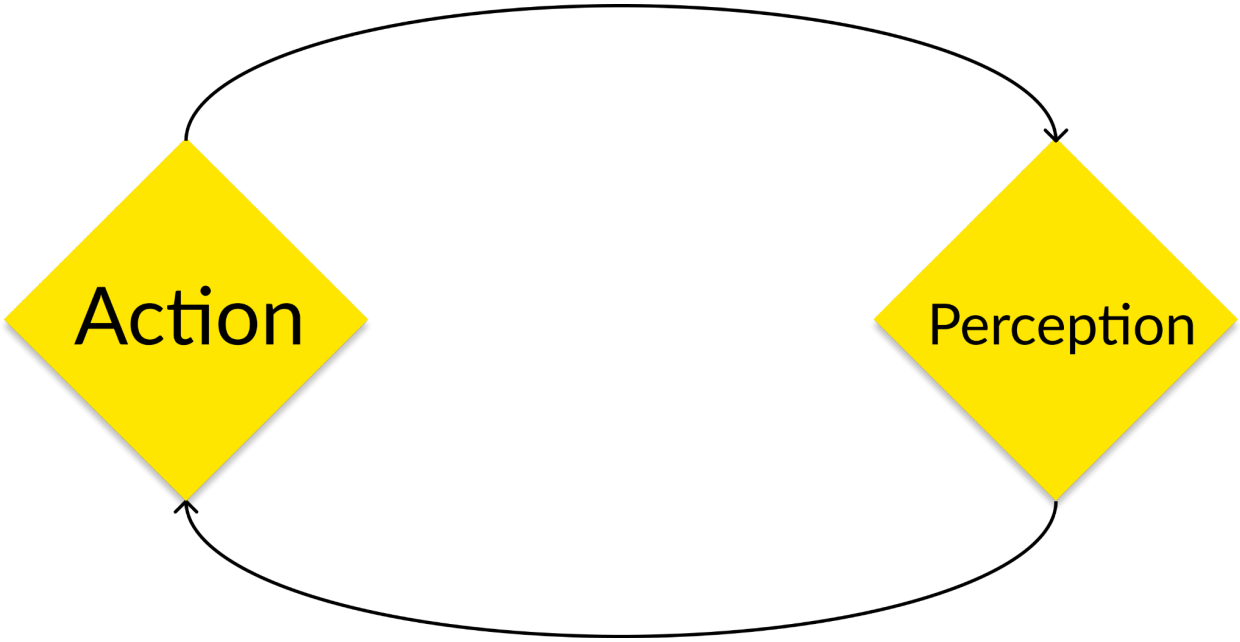
which will then inform my research design and analysis.

Enactivism and contemplative-somatic learning

This research follows an *embodied, enactivist approach* to STEM learning, which views education as a process of learning to move in new, task-effective ways attuned to the natural-cultural environment. At the heart of enactivism is an understanding of cognition as *perception-for-action* (Varela et al., 2016). As Abrahamson describes, "The core of mathematical knowing is not what you know *about* a concept but your capacity to *enact* the concept as perceptuomotor activity" (Abrahamson et al., 2021, p. 164). Thus, an enactivist pedagogy aims to create opportunities for learners to grasp and ground their understanding of phenomena in their embodied experience via sensorimotor participation. To learn is to move in, with, and through the world in congruous ways. The task of *embodied design* in education is to construct tasks for exploring and refining the coordination of perception and action to most effectively accomplish given objectives—known as *action-based learning* (Abrahamson & Sánchez-García, 2016; see Figure 1). Through this coordination, learners ground their conceptual understanding in meaningful sensorimotor experience and are readily able to grasp symbolic representation of content in relation to such formed sensorimotor schema.

Figure 1

The focus of an enactivist approach to action-based learning is the perception-action loop

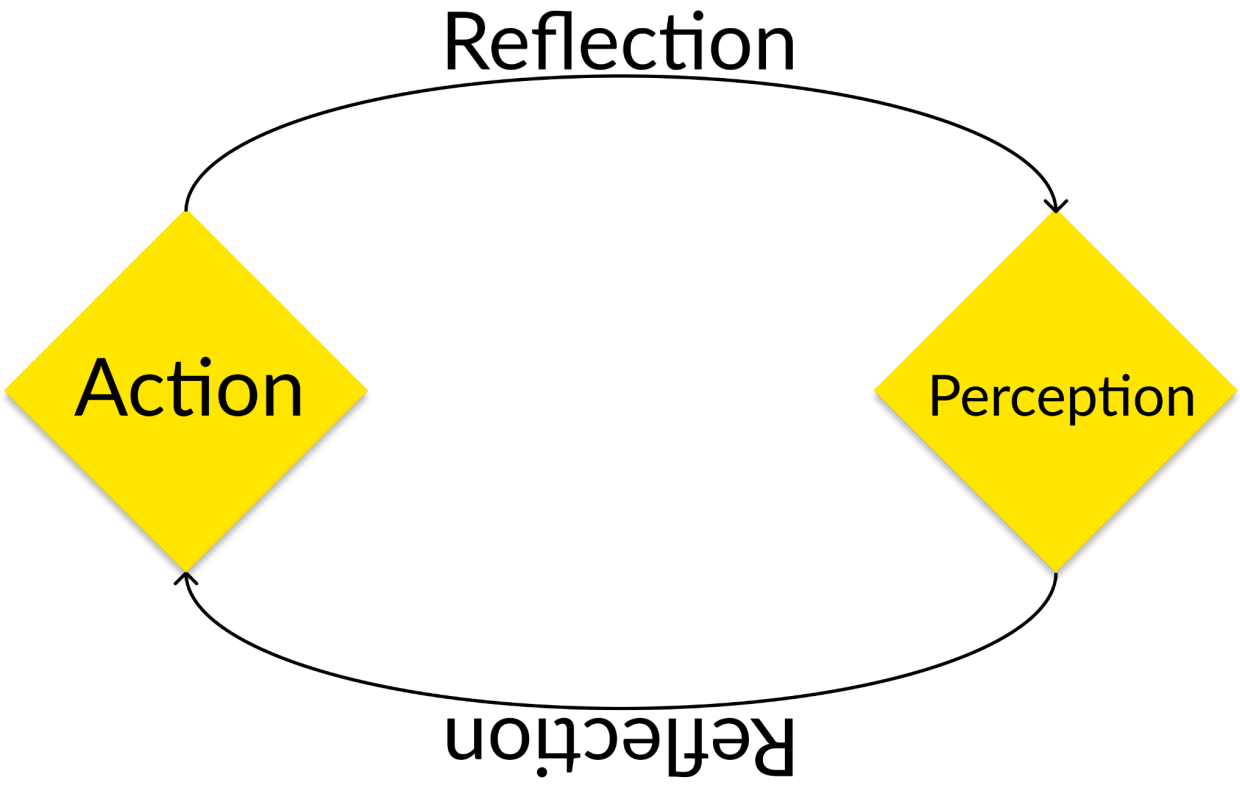


Furthermore, to deepen this action–perception coordination, an enactivist pedagogy must facilitate reflection on one's actions: "Meaning construction in embodied pedagogy involves a cyclical process of mindful action and reflection which shapes the learner and the space and spatial arrangements where action takes place" (Yiannoutsou et al., 2021, p. 3). To learn to

intentionally reflect is to learn to attend to one's own embodied nature and begin to develop an intimacy with one's own unfolding process of sense-making. Morgan (2018) describes this process as *contemplative-somatic learning* and calls for pedagogy designers to "include prompts to elicit this meta-awareness …. *to sense the process of change or learning as it occurred*…. tracing the steps of their learning to make cognitive meaning of their learning" (p. 5, emphasis added; see Figure 2). As Malafouris (2020, p. 6) describes, "it is our uneducated attention that lacks the ability to navigate the landscape of affordances …. and discover the cognitive life that the flow between the hand and the clay entails."

Figure 2

Contemplative-somatic learning emphasizes the role of reflection in the perception-action loop



This contemplative–somatic learning approach sets its pedagogical sights far beyond the typical anxiety-reducing, attention-enhancing, motivation-increasing focus of dominant contemplative-learning discourse. To be sure, such a reflective, relational, participatory approach likely would indeed address many of the root causes of such affective afflictions. However, as Abrahamson and Morgan (2016) argue, "As long as contemplative practice is applied only.... business-as-usual....rather than to deep embodied and pre-conceptual meaning making,....the field is only scratching the surface of contemplative practices and losing out on their very essence and gift" (p. 36). Contemplative–somatic learning has the potential to revitalize pedagogy by reanimating learners' relationships to not only the subject matter at hand but also to

themselves and, more broadly, to the more-than-human world.

Ecological dynamics, material-engagement theory, and kinenoetics

To holistically examine the relationship between sensorimotor material engagement and sense-making, this research draws on the theoretical approach of *ecological dynamics*. This approach, blending *dynamical systems theory* (Richardson & Chemero, 2010; Smith & Thelen, 2003; Spencer et al., 2012) with *ecological psychology* (Gibson, 1977; Richardson et al., 2008), frames learning as a complex self-organizing of subject–environment dynamical systems. In this perspective, learning emerges through: the coordination of many components, including the subject(s) and available affordances of the environment; self-organizing behavior, in that individual behavior is bound to the qualities of the collective system, without any central controlling component; and the emergence of coherent patterns via collective behavior not predictable from that of separate individuals (Abrahamson & Sánchez-García, 2016). In this regard, this research examines the emergent behavior of students in relationship to the physical materials made available in learning environments in the context of purposeful, task-oriented activities. Through this, the aim of this research is to qualify the effects that material engagement has on learners' subjective experiences, and to explore how material features affording "thinking as 'thinging'" affect students' sensemaking whilst learning (Malafouris, 2020; see Figure 3).

In order to qualify the unfolding process of materially engaged sensemaking, this research applies *kinenoetic analysis*, which bridges the gap between epistemology and ontology by examining the material imprints of the emergence of knowledge (Ross & Vallée-Tourangeau, 2021; see also Martin & Schwartz, 2005, on distributed cognition). In this approach,

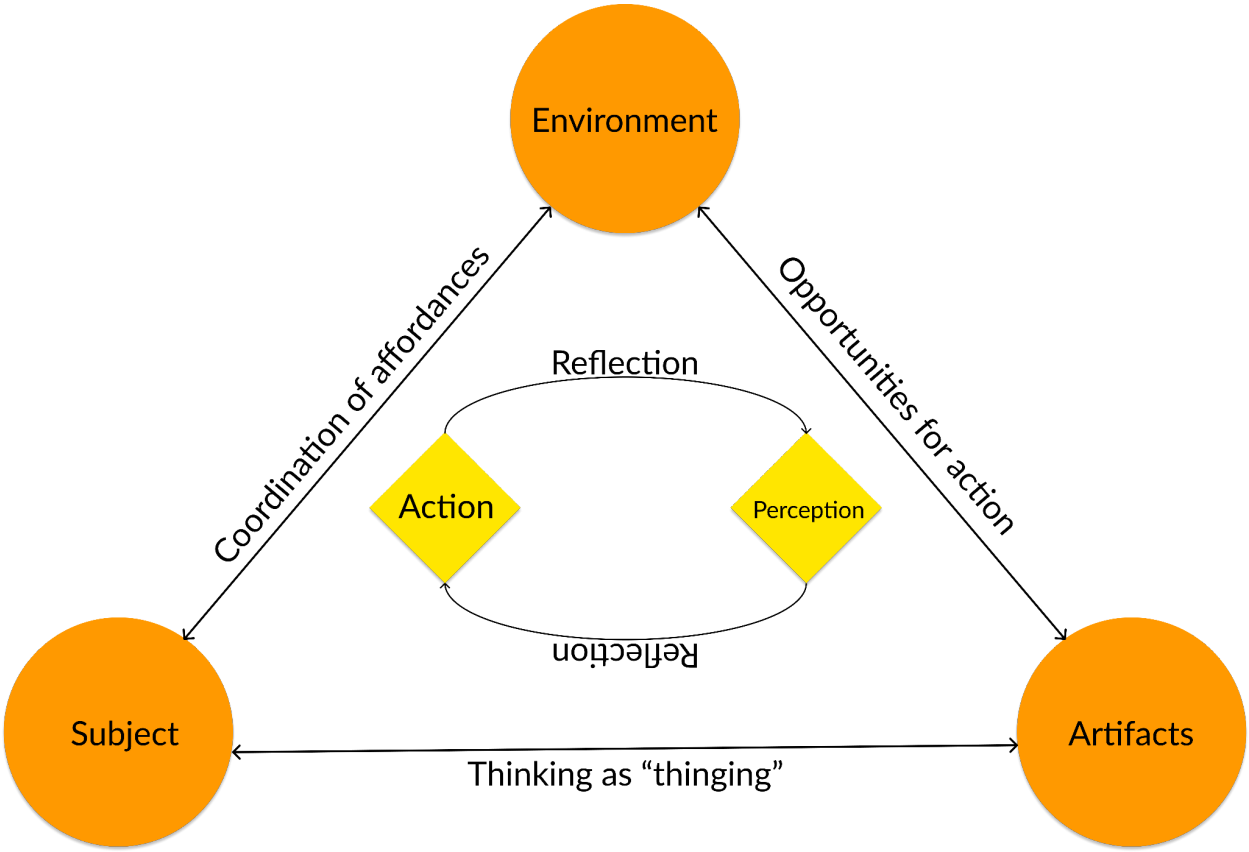
> the development of knowledge, the genesis of new ideas…. proceeds on the basis of gradual transformations of physical objects along a contingent arc. Each change in the object triggers new perceptions and new actions (p. 2)

This materially engaged lens supports a core aim of research in embodied design for learning:

> empirical data evidencing the micro-emergence of mathematical concepts constituted as perception-for-action. [Researchers are enabled to] literally witness, track, and anticipate how new sensorimotor patterns coalesce into dynamical stability, how these patterns come forth into students' consciousness….and how students appropriate conventional mathematical tools to stabilize, refine, and document their actions. (Abrahamson et al., in press, p. 24)

Figure 3

Ecological dynamics and the relationship between subject, environment, and artifacts



Metarepresentational competence

Bamberger and diSessa (2003) investigated how students model musical experience in naïve semiotic expression. They state, "The essence of understanding some scientific concepts lies precisely in developing strategies that allow for the perception of 'noticing' the relevant entities and relations" (Bamberger & diSessa, 2003, p. 134). The authors emphasize that such noticing does not occur spontaneously. Indeed, it is this capacity for noticing that differentiates a domain expert from a novice.

From Bamberger and diSessa's work emerges an important focus of this research: how students draw salient features from the ephemeral, sensuous substance of their experience to shape their evolving understanding. To trace this unfolding sense-making, students must both maintain an experiential grounding in the source experience of their perception, while also attending to the constitutive components present. Students are asked to unpack their felt experience in order to reflect on it, and then to repack it as representation.

Somaesthetics, neurodiversity, and embodied semiosis

Höök's 2018 "Designing with the Body" introduces *soma design*: "a theory and practice of design that accounts for the unity, rather than the separation, of mind and body….[that] engages with bodily rhythms, touch, proprioception, bodily playfulness,….our values, meaning-making processes, emotions, and ways of engaging with the world". Höök draws attention to the

potential of design to support a radical opening to the whole of both being and interbeing, by examining the orchestration of the individual and the social self in relationship to materiality. This *somaesthetic* approach to design—rooted in holism and sensorimotor meaning-making—runs parallel to certain perspectives on the embodied semiosis of neurodiversity. Sterponi (2019) emphasizes the significance of the semiotic dimension of language—tone, rhythm, prosody, texture—as the translinguistic materiality of words and phrases, which grounds linguistic signification in the sensuous, felt dimension of experience. This aspect of expression runs central to the framing of neurodiversity offered by Nolan and McBride (2015), which recognizes an *embodied semiosis* for which the body is "the nexus of lived experience and culture, as a portal, a site, an experience" (Connolly 2008, p. 242).

Both somaesthetics and neurodiversity draw attention to the sociocultural influences on the normativity of language and phenomenology: processes of individual and collective sense-making are "fundamentally guided and influenced by the social and cultural context….to the point that we unconsciously assume verisimilitude," (Nolan & McBride, 2015, p. 4). This research aims to explore possibilities for an educational environment that embraces a somaesthetic queering of pedagogical semiotics and conceptual sense-making, welcoming a phenomenology lost to the "disembodied and non-intuitive notions of feeling, sensing, communicating and relating that are characteristic of the socially and culturally derived sensory integration of the neurotypical," (ibid, p. 4).

Phenomenology, transmodality, and the felt dimension of experience

Synaesthesia is the experience of activity of one sensory modality triggering activity in another, such as *tasting sound*. Though considered rare, Merleau-Ponty argues that synaesthetic perception is the rule for human experience, and that it is a core quality of our perceptual phenomenology. Merleau-Ponty (2013) is concerned that our civilization has "unlearned how to see, hear, and generally speaking, feel" this synaesthetic quality of our experience (p. 229). Our senses are in constant intercommunication and overlap with one another, and it is precisely the *transmodal* sensorial submodalities Petitmengin (2021) draws attention to that facilitate this dance—the dynamic textures, rhythms, and intensities that vitalize and animate our sensorial experience.

Petitmengin's work involving the pre-reflective dimension of subjective experience substantially informs this research, as a means of both structuring the materially facilitated self-reflective interview task (see the Methods section for details) and guiding the focus of qualitative analysis. Petitmengin (2007, p. 54) offers a description of the *pre-reflective* or *felt dimension*: "[It is] gestural and rhythmic, has precise transmodal sensorial submodalities, and seems to play an essential role in the process of emergence of all thought and understanding." Of particular interest to this research project is the quality of *transmodality*: the silent stratum of lived experience, always with us, "gestural and quivering," "endowed with a texture [and rhythmic] contrasts of densities and intensities" (Petitmengin, 2021, p. 173), fundamental to our sense-making in the world (see Figure 4). An example of this silent stratum of lived experience includes the description Terence Tao (2016) offers of his sense-making around partial differential equations:

> I find there is a rich zoo of colorful physical analogies that one can use to get a grip on a problem. I've used the metaphor of an egg yolk frying in a pool of oil, or a jet ski riding ocean waves….In one extreme case, I ended up rolling around on the floor with my eyes closed.

Another, from Albert Einstein, in relation to his internal experience leading up to the theory of relativity:

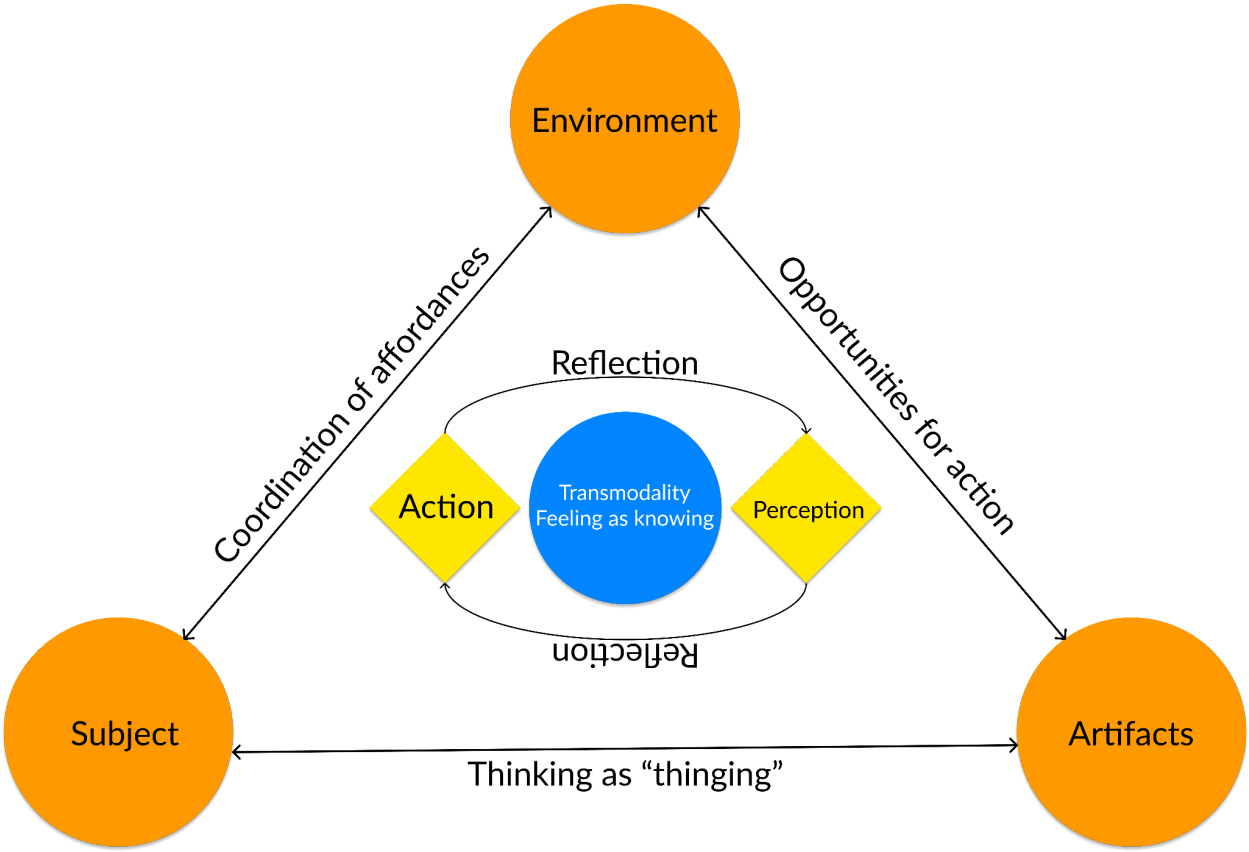
> For all these years there was a feeling of direction, of heading straight for something concrete. It is of course very difficult to express this feeling in words. But I had it in a sort of overview, and in a certain way, visually. (Holton, 1998).

Drawing on these aforementioned philosophical and critical-pedagogical positions and applying them in the form of transformative education, this research agenda posits a design conjecture that *materials that afford engagement emphasizing texture, rhythm, and intensity enable a deeper subjective sensitivity to the felt dimension of experience*. Beneath the surface of a learner's new conceptualization lies a feeling-as-knowing rooted in unfolding phenomenology, their "rapid premonitory perspective views of schemes of thought not yet articulate" (James, 1891, p. 254–5). Might this vague, elusive, murky pre-reflective substance be attended to and expressed with more clarity through particular forms of material engagement, revealing thoughts, ideas, and concepts at the cusp of their emergence? For

> each thing….has the power to reach us and to influence us….[and] is potentially expressive….[T]hus, at the most primordial level of sensuous, bodily experience, we find ourselves in an expressive, gesturing landscape, in a world that *speaks*. (Abram, 1996, p. 81)

Figure 4

Transmodality and feeling as knowing at the root of experience



Gesture and egocentric perspectivity

Critical to this pre-reflective cognitive space is the role of gesture, both external and internal. Gesture, the process of putting forth thoughts, feelings, intuitions, into the world and in response to the world, in a state of exploration and transformation, "may reflect new ideas that learners are 'working on'— ideas that they are considering, evaluating, or consolidating" (Abrahamson et al., 2020, p. 10). Gestures serve to highlight, often unconsciously, "aspects of….tasks that learners are focusing on" (ibid, p. 10), revealing details of one's phenomenological experience that are being attended to and are deemed relevant to the task at hand. As a tool for conceptual development, gesture supports a plethora of cognitive strategies, including activating, manipulating, organizing, and schematizing spatio-motoric and abstract information (Kita et al., 2017). Gesture becomes an invaluable resource for gaining insight into one's cognitive processes, both as a tool for self-reflection and for educators (*in situ*) and learning science researchers (*post facto*), "rendering the visible kinesthetic for the gesturer and the kinesthetic visible for the perceiver. The gesturer, that is, feels what she speaks; the perceiver sees what she feels" (Young, 2021, p. 93).

Gerofsky's 2011 work traces the enacted embodiment of mathematical concepts via gesture. In her work, she found particular qualities of embodied gesture be correlated with student attentiveness to and engagement with mathematical features of graphs. Specifically, there existed a spectrum of embodied gesture that corresponded to a spectrum of conceptual

understanding. She differentiated the two ends of the spectrum as "seeing the graph" versus "being the graph": an *allocentric* reference frame versus *egocentric*. Do students feel themselves as external observers to the representational structure, or as embodying the structure itself?

Kita et al. (2017) make the distinction between gesture and action, describing gestures as being representational and used to schematize information, while often being free of physical constraints and not leaving a physical trace. These latter two features of gesture hold imperative implications for educational design: how might an interactive space be designed that affords the physical freedoms necessary for gestural expression, while overcoming the inherently ephemeral nature of gesture that makes it difficult to be held onto for inspection and exploration? In other words, how can we create a space that bridges the divide between the felt and the known, allowing us to capture and examine the subtle nuances of movement and expression? How can we design an environment that fosters a deep sense of presence and engagement, while also enabling us to reflect on and analyze our experiences? In a word, how do we arrest gesture? These are the questions that lie at the heart of the challenge of designing an interactive space for gestural expression—a challenge that demands not only technical expertise, but also a deep understanding of the complex interplay between the subjective and the cognitive realms of human experience.

Clay: an expressive medium for sense-making

Now, dear reader, let us take a step back and consider which media may provide the affordances potentially valuable for the focus of research at hand. In essence, this research design aims to elicit a reflective, contemplative conversation between the learner and expressive media (Bamberger & Schön, 1983). What media may both afford tangible exploration of students' subjective, internal felt experience, while also providing learning scientists and educators insight to the physical shape of gestural content over time? Clay, I submit, is a semiotically unconfined medium for documenting modulation in students' sense-making experience. As such, I hypothesize, clay could enable individuals to express their pre-symbolic imagery and inner gestures outwardly—gestures emergent in, and formative of relationship to multimodal perceptual experience. By this token, I submit, clay could afford a concretization of the trajectory of understanding via material representation, acting as a medium to record an emerging morphology of perceptual phenomenology: a record potentially rich in meaning for learning scientists, educators, and students all. Clay could make visible tacit semiotic activity and extend its fleeting life, allowing for reflection, exploration, refinement, and alteration. Specifically, clay may capture pre-symbolic gestural content, turning the ephemeral feeling-as-knowing concrete: an invaluable affordance for learning scientists and education designers to glean insight into the nature of how humans learn and make sense of the world.

Thus, applying enactivism, ecological dynamics, material-engagement theory, and phenomenology, this research examines what particular forms of noticing clay invites during the unfolding formation of transmodal semiotic systems.

Literature review

Enactivism and mathematics

Research regarding enactivist approaches to mathematics education is emergent (Abrahamson, 2022; Hutto et al., 2015; Maheux and Proulx, 2015; Palatnik and Abrahamson, 2021; Pirie and Kieren, 1989; Pirie and Kieren, 1994; Proulx, 2013; Roth and Bautista, 2011). Of particular note is research which includes both the subjective and affective dimensions of experience within enactivist design of pedagogy. Chiu et al. (2022) introduces affect-focused mathematical teaching, aiming to enhance students' affective performances in mathematics learning via an enactivist perspective. However, the framing "affective performance" is problematic in its reductive attitude: what Morgan and Abrahamson refer to as the "business-as-usual" focus on improving scholastic performance without recognizing multidimensionality of the learning experience (Morgan & Abrahamson, 2016). This research aims to expand the consideration of affect in education beyond that of supporting or hindering content learning. A number of other practitioner-oriented research projects apply enactivist theory to mathematics education design, however with little to no emphasis on the potential interplay of various sensory modalities and semiotic mediums within such environments (Abrahamson, 2022; Palatnik & Abrahamson, 2021; Videla-Reyes & Aguayo, 2022). Much of this enactivist research homes in on the relationship between sensorimotor engagement and resultant semiotic systems, with less emphasis on the characteristics of semiotic media mediating representation.

Contemplative mathematics

Work on contemplative approaches to mathematics learning is emergent, with four relevant papers between 2007 and 2016. The inclusion criteria used to determine the relevance of search results were if the paper applied contemplative techniques or a contemplative lens to teaching and learning mathematics in ways not focused on affect regulation (for example, mathematics anxiety). The first, "*On Contemplation in Mathematics*" (Wolcott, 2013), explores possible benefits to increasing one's phenomenological self-awareness whilst partaking in mathematics research. This paper was practitioner-oriented, addressing mathematics researchers and educators. The knowledge base here was drawn from the researcher's firsthand experience as a mathematics practitioner and 10th grade educator, with the primary methodology being a case study of said firsthand experience and ad-hoc surveys gathered from students at the end of each week of instruction. In a similar context, Brady (2007) offers an experiential report of applying a contemplative approach to teaching 10th grade mathematics, with an emphasis on examining the curriculum content that was contemplative in nature. However, neither paper delved into the implications of contemplative pedagogy as a means of conducting learning-science research, which this research agenda aims to do.

On the other hand, the collaborative work of Morgan and Abrahamson shifts the focus of attention to "deep embodied and pre-conceptual meaning-making" (Morgan & Abrahamson, 2016, p. 36) and the potential for a contemplative-somatic pedagogy to elucidate "how cognitive structures emerge from sensorimotor activity to conscious reflection" (Morgan & Abrahamson, 2018, p. 2). Building on their research agenda, my study aims to use a contemplative-somatic

approach to further flesh out the gap between pre-symbolic notions and conceptualization via case study work.

Clay and mathematics

Clay has seen little research within the mathematics domain, and STEM more broadly. In order to explore the pedagogical affordances of clay as an expressive medium, the domain of sensorimotor arts therapy provides a host of relevant research. Sensorimotor arts therapy explores the "intimate relationship between physiological and psychological dimensions of human experience" (Hansen, 2018, p. 1). Specifically, clay affords a reasoning from within the physiological-psychological dimension of experience via one's haptic engagement: "exteroceptors and interoceptors become naturally stimulated, and every movement of the hands provides instant feedback to the brain [...] allowing non-verbal access to psychological and sensorimotor processes" (Elbrecht & Antcliff, 2014, p. 1). Much research has been done exploring the affective dimension of this physiological-psychological relationship, such as emotional regulation and positive affect priming (Klein et al., 2020; Leone et al., 2018; Meighan, 2021). On the other hand, the processes by which cognitive understanding develops vis a vis this physiological-psychological relationship of human experience remains less researched.

Design solution and research questions

The essential design conjecture is such: providing students with appropriate media to express their perceptual experience of kinematics may solicit their phenomenology of movement, materializing the perceived affordance of ephemeral sensory engagement. Divorcing the object of manipulation (clay) from the object of inquiry (a moving object) may occasion students guided opportunities to unpack observed kinematic phenomena into its extensive components and then repack it, while maintaining their experiential grounding in the source experience of movement that their clay constructions are to model. To this end, this design aims to elicit a conversation with the material (Bamberger & Schön, 1983)—in particular, a conversation with clay, an easily available medium with rich haptic affordances. The conversation begins by establishing a contemplative space for learners that emphasizes sensitivity to their tactile-perceptual experience while handling clay, drawing on aforementioned work related to gesture, felt experience, and contemplative-somatic learning. Then, clay is used as a medium to elicit tacit transmodal elements of learners' perceptual phenomenology, in order to surface vital aspects of the felt experience of visual perception. In this way, clay engagement during observation of kinematic phenomena acts as a bridge from the preconceptual-somatic realm to semantic-semiotic: an "exercise that enable students to firm up preconceptual somatic meanings in color, shape, rhythm, and form before shaping them into words, [...] centering on the role of formulating language "inside-out," (Morgan & Abrahamson, 2018). In other words, clay serves as a conduit for feeling-as-knowing in learning contexts.

This research aims to explore the following questions:

- What is the relationship between available expressive media and potential semiotic systems during conceptual learning?
- What is the pedagogical potential inherent in attending to the felt dimension of

experience in learning?

Methods

Participants

This research worked with eighth-grade students (all 13 years old) from a public middle school in Oakland, CA (n=7). Students were of diverse racial and socioeconomic background as well as varied mathematics skill level, as indicated by their teacher.

Materials

Throughout the interviews students were provided with clay[2]. Students were free to choose as much clay as they wished, and which colors[3], adding or subtracting material as the interview unfolded. Furthermore, each student was provided with a desktop dry-erase tablet, upon which to place their clay models, along with four dry-erase markers (red, green, blue, and black). Interviews were conducted in-person with interviewee and interviewer sitting side-by-side in chairs in front of classroom desks. A laptop computer was used to display animations, and video footage of both interviewee and interviewer was taken on a tripod-mounted mobile phone.

Procedure

A semi-structured task-based clinical interview protocol was planned to take 45 minutes, and it consisted of two main phases. To begin, participants were offered a large ball of clay (participants used various colored clays, all the same density and plasticity). With the clay in hand, participants were: (1) guided through a contemplative exercise meant to bring attention to the felt experience of working with clay; and then (2) asked to model their visual perception of multiple animated scenarios of accelerating objects.

(1) The contemplative exercise drew heavily from Petitmengin's descriptions of interior gestures as important precursors to becoming sensitive to the felt experience as well as Morgan's work in contemplative-somatic pedagogy. Namely, the participants first were guided towards stabilizing their attention, through synchronizing their manipulation of the clay with their in- and out-breath. Participants were instructed to find some action to do with the clay on each inhalation, and another action to do with the clay on each exhalation. Emphasis was put on allowing the action to come naturally and intuitively. After some time with this stabilizing exercise, participants were then guided towards shifting their attention from what they were *doing* with the clay to how it *feels* to be working with the clay. This was done by prompting the participants for descriptive words of their physical, emotional, and mental experience: how does the clay feel in the hands? Are any emotions or feelings coming up while interacting with the clay? Are there any mental images, sounds, or memories surfacing? Finally, participants were nudged towards adopting a specific attentional position of receptivity

[2] Roma Plastilina™ non-drying sulfur-based soft modeling clay from Chavant

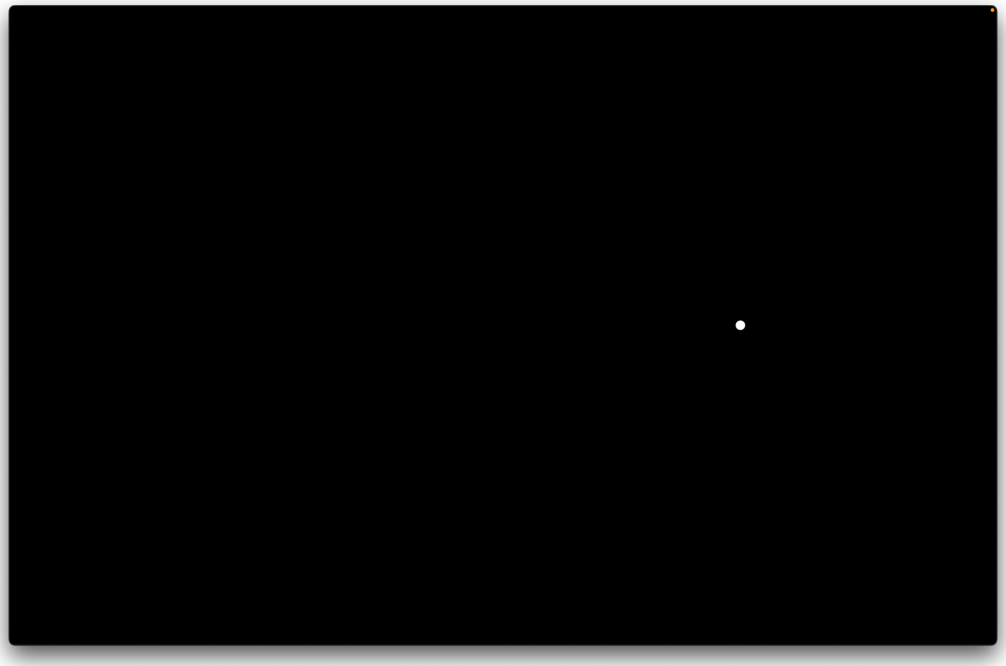
[3] Colors offered were earth-tone shades of brown, off-white, green and blue

towards their felt experience with the clay, inviting themselves to feel touched by clay as much as they themselves were touching the clay. This prompt was intentionally left open-ended, and often came with an acknowledgement of its strangeness, with encouragement to simply invite that notion in without much rational thought or judgment.

(2) Following this, participants were asked to observe an animation on a computer screen. The animation consisted of a small white circle, moving from left to right across a black background (see Figure 5; see Appendix C for source code). After observing the animation, participants were asked about their subjective experience while watching and were then invited to shape the circle's behavior of motion with the clay. Participants were also asked if there were perhaps any sound they would give to the circle's movement. Finally, participants were prompted to model what they observed so that their teacher, if she came later and saw the model, would know what they had observed. This prompt is taken directly from Bamberger's early work exploring semiotic representation. This prompt is intended to bring forth perceived features of the observed phenomena that were personally relevant to the participant's perceptual phenomenology as pertaining to their understanding of the semiotic task at hand. Following the modeling activity, the interviewer and participant openly discussed what the participant had done and why (see Appendix X for the interview protocol).

Figure 5

Still-frame of Animation of a White Circle, Moving from Left to Right across a Black Background



This latter process was repeated for four animations, each of which showed the circle moving at a different rate of acceleration (see Table 1). Two scenarios showed positive acceleration at different rates, one showed negative acceleration, and one showed zero acceleration (constant velocity). Each clay model participants had produced was laid out next to the previous ones, so that after modeling all four scenarios, a total of four models lay side-by-side. Participants were given permission to change any of their models at any time. Note that discussion of the animations and models are always in relationship to each other: for each participant, Model 1 followed the viewing of Animation 1, and so forth.

Table 1
Rates of Acceleration for each Animation

Animation #	Acceleration (initial velocity: 60 pixels / second)
1	.6 pixels / second^2
2	2.4 pixels / second^2
3	-.6 pixels / second^2
4	0 pixels / second^2

Throughout the process, the researcher employed an interview technique inspired by microphenomenology. *Microphenomenology* is a first-person subjective interview technique whose purpose is to make explicit the implicit aspects of the participant's experiences (Petitmengin, 2006). By conducting micro-phenomenological interviews across a number of participants, the author sought to gather recurrent phenomenological markers and to identify generic structures of subjective experience, in order to paint a fine-grained picture of the dynamic qualities of meaning-making. The author adapted the microphenomenological interview process, originally formulated for adults, to make it appropriate for the young participants. Moreover, whereas the microphenomenological lines of questioning[4] are regularly presented only after an activity has been completed, this study's procedure interspersed the questions within the modeling activity. This was done in order to employ the immediacy of participants' phenomenology to both maintain and deepen their attunement to the felt dimension of their experience.

Data Gathered
The data gathered consisted of audio–video footage of the participants' interviews as well as photo images of the final array of four models for each participant. Transcription of each participant's verbal and gestural utterances was later generated from the footage.

[4] e.g, *When you did this, what was that like for you?*, or, *How was it for you to do that?*

Data Analysis

The author employed design-based research analysis, drawing from elements of microphenomenology analysis and kineonetic analysis (see Conceptual Framework). Thus, particular emphasis was given to participants' linguistic descriptions of their subjective experience, in conjunction with their gestures and handling of the clay. Emergent patterns and recurrence of experiential reports, gesture, and clay modeling were categorized into broader themes. Data extracts used in this paper were selected based on relevance to the research questions outlined in the previous section. To aid the reader in understanding the context of participants' responses, the researcher's prompts were included when relevant.

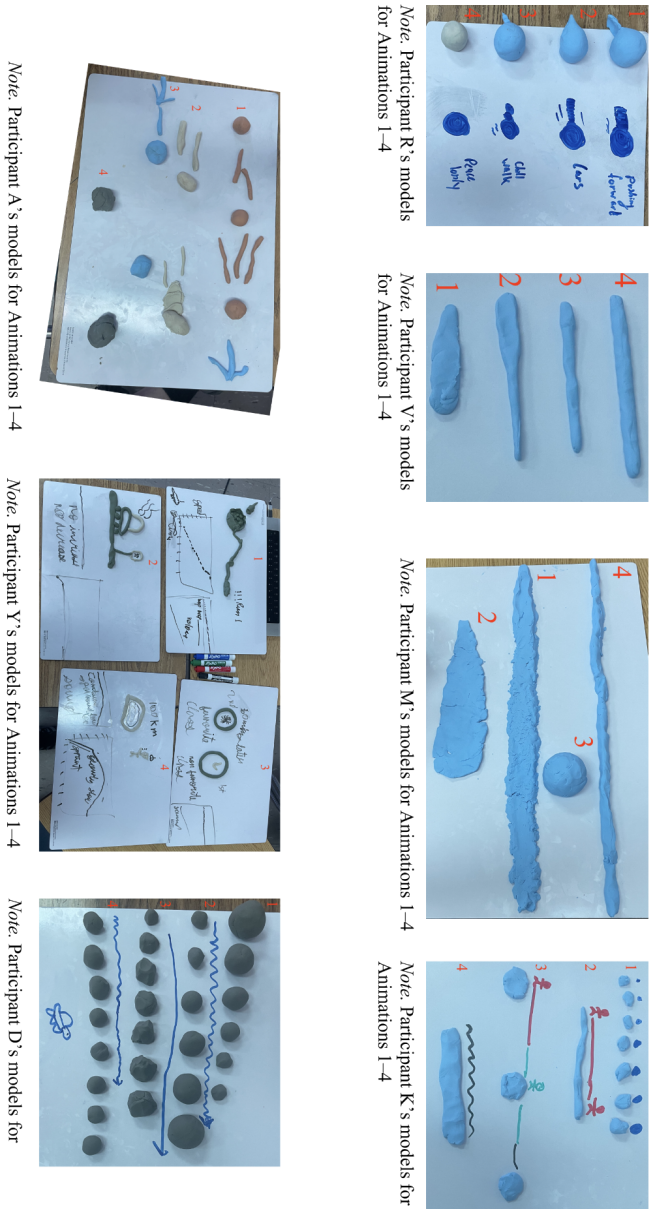
Ethics

Identifiable features of the individuals were blurred in video and photography footage, and names were redacted and replaced with pseudonyms to ensure anonymity. Students were selected randomly. Consent was obtained for using participant data in the analysis of the research, in accord with obtaining IRB approval from the relevant university department.

Furthermore, the area of focus in this research is the deep, underlying roots of our unconscious sense-making unfolding moment-to-moment. The process of becoming intimate with the felt dimension of one's experience does not promise a lack of negative emotional, psychological, or physiological arisings – as any experienced meditator would likely confirm, this work has the potential to stir up an abundance of underlying, potentially unresolved psychological material. Therefore, this contemplative realm must be explored with utmost sensitivity, respect, and a commitment to holistic well-being. In this way, this work takes as its orientation an ethics of care and compassion, both for the participants and for the larger community of educational practitioners and learning scientists. The author is an experienced contemplative practitioner and is trained as a trauma-informed meditation instructor.

Results

Figure 6
Participants' Models 1-4 for Animations 1-4, Labeled in Red



Note. Participant R's models for Animations 1–4

Note. Participant V's models for Animations 1–4

Note. Participant M's models for Animations 1–4

Note. Participant K's models for Animations 1–4

Note. Participant A's models for Animations 1–4

Note. Participant Y's models for Animations 1–4

Note. Participant D's models for Animations 1–4

Egocentric immersion in observed phenomena

During the interviews, participants' reports frequently indicated a strong sense of being figuratively transported into related, sensorially rich scenes as they observed the kinematics animations. What was, at the outset, a relatively sensorially-drab scene—a white ball moving across a black screen—metamorphosed for participants into a scene rich with character, affect, and meaning. Animation 2 reminded participant Y of the subjective warping of time when stimulated versus bored.

> Researcher: "Yeah. So what was that like for you?" (30:30)
>
> Y: "It kind of reminds me of time, like how when you're in a class and you don't know anyone there and it feels like it takes forever, and then you're in another class and you do know people and you start talking and then class is suddenly over." (31:00)

For participants A and R both, Animation 3 evoked a sense of slowing down after a run.

> Researcher, to A: "How would you feel if you were moving like that? What would your body feel like?" (24:15)
>
> A: "...after a race, where you were running super fast then you slowed down, like you're tired after being super fast." (24:40)
>
> R: "Model three feels like running at first, for example, like running to your friend and then you get tired and start walking, like a chill walk because you're trying to get back your stamina." (30:15)

Animation 4 transported participant R to a sense of "walking by a river by yourself—no birds, no nothing, just water and trees." (29:50)

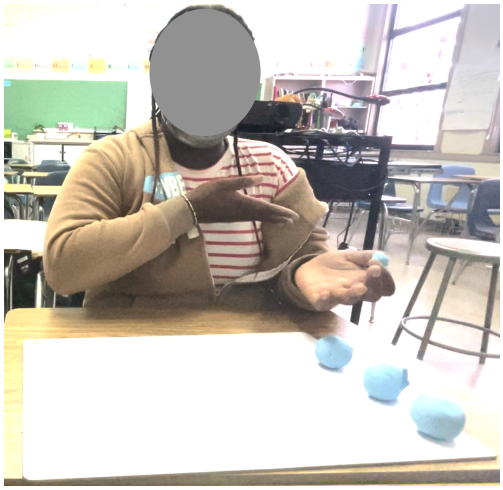
Furthermore, multiple participants used language that suggested an egocentric perspective of the scene: being embedded within the scene rather than being observers of the scene. This perspectival language suggests that participants felt themselves as active agents in relationship with the kinematic phenomena.

> Researcher: "I want you to shape the clay in the same way that that animation was moving" (19:10)
>
> M: "For me, when I looked at it, I felt, it was small at the back and then it started to grow the more it got close." (19:40)

M felt that the object moved towards them, starting "small at the back" and then growing as "as it got close" (cf, Abrahamson et al., 2012, pp. 68–72). This is striking in that, though the circle in the animation neither changed shape nor moved in any axis besides the horizontal, M still felt it to be growing and moving closer.

Similarly, participant R felt themselves moving along with the animation, their sense of body image carried with the unfolding of the scene (see Figure 7).

Figure 7
Participant R Gesturing Where They Felt Themselves Moving



> Researcher: "What is that like for you?" (22:43)
> R: "I feel like I was also moving with it, like a phantom body…its like I feel like I'm moving but I'm not actually moving at all…[*gesturing head to chest*]...moving at the same pace as it, maybe a little bit behind, because when it started, I just started." (23:00)

Participant M also suggested an immersive experience with the animation. In particular, what is notable is M's usage of first-person language (see Figure 8):

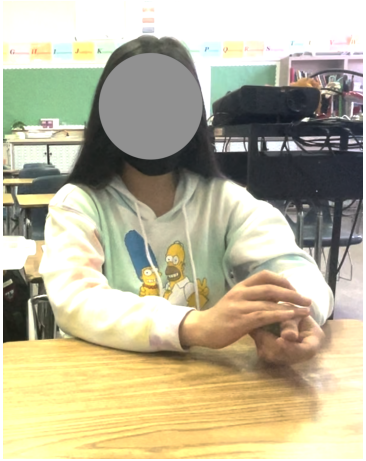
> Researcher: "Can you shape the clay so it feels like it's moving?" (20:40)
> M: "That kind of makes *me* feel like *it*." (20:50)
> Researcher: "So what do your hands want to do with the clay now?" (27:55)
> M: "*I* kind of want to go upwards, like when you shoot a flashlight and the beam of light goes upwards and kind of spreads a bit, like it's increasing in width as it goes up." (28:00)

Figure 8
M Gesturing a Felt Sense of Upward Movement

Shifting awareness from seeking to receiving

Recall that during the preparatory, contemplative stage of the protocol, the interviewer invites the participant to allow themselves to feel shaped by the clay as much as they are shaping the clay. Most of the participants expressed confusion as to how they might respond to this invitation. Notwithstanding, analysis revealed apparent changes in the participants' handling of the clay in response to the invitation, which suggests that, indeed, some shift of awareness occurred. For example, following the invitation, Participant Y's handling of the clay becomes significantly more subtle, touching and pushing gently, as they share, "It's gripping onto me." (10:44, see Figure 9).

Figure 9
Y Holding the Clay Still Against Their Skin: "It's gripping into me" (10:44)



Participant A shifts from rapidly squeezing the clay to simply holding the clay stationary:

> Researcher: “How do you feel with it?” (7:08)
>
> A: “I feel like focusing more on the clay puts me in a more relaxed state.” (7:13)

Participant M shares an experiencing of looseness, and of a sense of balance that emerges from the loosening:

> Researcher: “So I want you to invite the clay to be shaping you as much as you're shaping the clay” (15:30)
>
> M: “It feels really loose, like my hands feel really loose. When I push, I let my finger be pushed back just a little bit. It’s like equal force, like the thought of an equal force makes me feel calm.” (15:52)

This shifting awareness towards one of receptivity to the senses is significant in that it prepares the ground for more embodied, somatically grounded semiotic modeling in the next stage of the interview.

Affective relationship to materiality and to perceptual phenomena

Participants communicated an overwhelmingly positive affective valence while working with clay. Both M and V reported a sense of the activity offering a welcome respite to the busyness of the day.

> Researcher, to V: “What does it feel like?” (5:00)
>
> V: “I feel more relaxed, mostly in my hands. As the day goes, the hand is always busy doing something, writing.” (5:08)

> Researcher, to M: “How are you feeling with it?” (10:50)
>
> M: “I find it calming because most of the time we are rushing most things and don’t pay attention to the little things in life, and when you really focus on it, you find new details.” (11:02)

Other verbalizations of affective experience, after watching the animations, include “relief” (A, 10:05, Animation 1), “surprise” (V, 14:50, Animation 1), “slower, calm” (K, 21:20, Animation 3), and “loneliness, not like a bad kind of lonely but a lonely where you’re at peace” (R, 29:50, Animation 4).

Participant A noticed a relationship between their sense of calmness and the intensity of handling the clay, where the clay reflected their own affective state back to them:

> Researcher: “How do you know you're feeling relaxed? What is that like for you?” (25:40)
>
> A: “I could tell when I was calm, because, before, I was messing with the clay a bunch more, but when I was watching the video, I was slowing down with the clay.” (26:05)

Clay also served as a lens into Participant K's processing of their affective landscape. Following the prompt to allow the clay to counter-shape them, K reports a sense of letting go that also prompts some fear. While K is quiet, in an apparent self-reflective state, they are rotating the clay in their hands. When they begin describing their experience, they stop rotating the clay and hold it still.

> Researcher: "How does that 'not worrying' feel?" (5:15)
> K: "It's like… scared, but a letting go feeling. I feel a little scared, because I'm not letting my brain think for me, but it feels good, because it clears my head." (5:30)

In a similar vein, after observing the first animation, K holds the clay stationary while they quietly reflect on their experience. When they begin sharing, their interaction with the clay again becomes more dynamic:

> Researcher: "How did you feel watching that?" (10:40)
> K: "Like you're in a scary movie and something bad 'bout to happen—like a jump scare." (10:46)

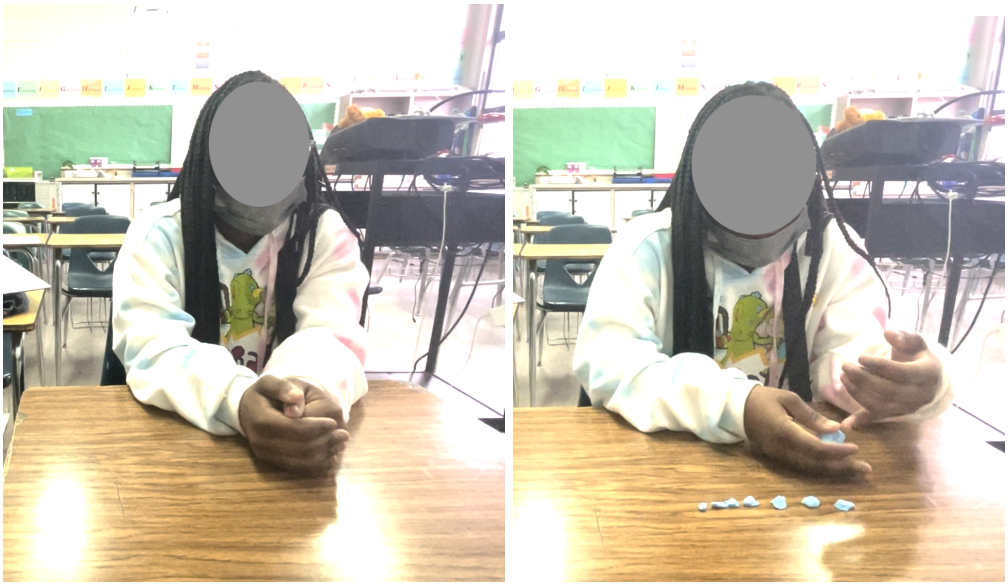
K then begins squeezing the clay with an increased intensity while describing their felt sense of anticipation.

> K: "Like a feeling. Like be prepared. Yeah." (11:00)
> Researcher: "How did you know you were feeling that? What was that like?" (11:10)
> K: "I feel it somewhere in my body, in my heart, like oh you finna [are going to] get scared." (11:24)

After sharing, K hides the clay between their hands, as if sheltering it (see Figure 10). When the researcher shifts the focus with another question, K begins again dynamically engaging with the clay (11:52–12:00). Finally, when asked what the experience was like for them to view Animation 2, K drops the clay from one hand to the other, gently touches it with their pinky, and then spontaneously squishes it intensely with the other hand: "I felt confident" (15:46).

Figure 10

Participant K Hiding Clay Between Their Hands after Describing Their Anticipation, and then Gesturing a Sense of Confidence



Accessing the felt dimension of experience

For many participants, the animations elicited vivid felt experiences. Often, participants used a combination of direct description and metaphor when sharing about this felt dimension of their experience. When asked whether M felt anything else in their body while molding the clay, they described a tingle in their calves, akin to the legs falling asleep, that is soft and peaceful:

> Researcher: "Is there anything else that you're feeling in your body while you're doing this?" (13:20)
>
> M: "It's a weird sensation in my legs when I spread [the clay]. Like a soft little tingle, in the lower part, the calves, in the back of the calves. Almost like when your leg falls asleep, like you fall asleep and you're half awake and half asleep. It's really soft. Like when you have a thought in the back of your mind and it just stays there. It feels peaceful, it's a peaceful feeling." (13:31)

Furthermore, M felt their interaction with the clay reverberating in their stomach, knotting and unknotting, as pressure is applied and released:

> Researcher: "So I want you to invite the clay to be shaping you as much as you're shaping the clay. What is that like?" (16:20)

> M: “I feel it a little in my stomach, like a tight knot, when I put some pressure, but then I mold the clay a bit and the knot goes away. When I squeeze, I can feel the knot, and when I let go, my stomach feels empty.” (16:42)

V described feeling a similar tingling to M when molding the clay. When asked about the tingling, they held the clay still in their hands, and were quiet for almost a minute:

> Researcher: “You said earlier that your hands are feeling a little bit more relaxed. What's that like? How's that feel?” (7:30)
> V: “It feels like, not exactly tingling but close to tingling” (8:20)
> Researcher: “Where do you feel that tingling?” (8:30)
> V: “close to where my wrists start…really hard to find words.” (8:40)

Holding the clay still during periods of self-reflection was common. K, when asked how the feeling of “good” was for them, rests the clay in their hands. After some time, they describe the feeling “like energy moving through my arms, like a battery.” (K, 6:50)

Some participants, not finding the words to describe these experiences, referred to other situations that *pointed to* what they felt, often accompanying the description with gestures. For example, after viewing Animation 1, M felt the same as when sighing and referred to an earlier mental image that had a peaceful association:

> M: “I would describe it as soft and pretty. I have the same image in my head of the grass and the tree. Like when you sigh, *ahhhhh*… it’s kind of like that when you sigh and you have a feeling inside of you.” (26:17)

Reflecting further on Animation 1, M described themselves as feeling like water flowing into larger and larger bodies:

> M: “When I saw this increasing, I felt like how a river leads to the ocean, like this could be a small stream, then a pond and a lake, then the ocean.” (44:35)

Animation 2, on the other hand, invoked an association of watching fireworks, and felt that same movement within them:

> M: “It felt a little less calming, but like when you see a firework go up in the sky, I kinda felt like how a firework shoots up in the sky” (29:03)

Animation 3 brought deep relief for M, and with it the felt sense of ease and contentment of accomplishment:

> M: [*takes deep sigh*] “It felt like something lifted off my shoulders, like *phew*, and I felt relaxed…like when you fix a problem and you feel so much lighter.” (33:30)

As M reflected on their experience having watched Animation 3, they were shaping the clay in their hand into a large flat circle (35:00). When asked how they would model Animation 3, they “just want[ed] to roll it into a ball, like no shape, no movement, just a ball.” (35:50, see

Figure 11). Compare this to their experience watching Animation 4, after which the clay spontaneously drops from their hands while they describe their felt experience of letting go:

> M: "In that one I just kind of let go, like, I let go of every thought in my head and I was really focused on watching the ball. My mind kind of told me to just let go, my mind was just like, *woof*" (35:50)

Figure 11

Participant M Shaping the Clay in a Circle After Watching the Third Animation

Other examples of signposts indirectly expressing the felt dimension of experience include V's description of Animation 1:

> V: "At first it was a bit surprising and then like the rest was okay." (15:00)
> Researcher, to V: "When you felt that surprise, how did you feel that surprise?" (15:06)
> V: "It's not a big surprise, but a weird feeling. Not exactly like a rollercoaster but similar to it, in your stomach." (15:10)

Y felt Animation 1 in the same way that a migraine appears and disappears suddenly:

> Researcher: "If you were to describe for me so that I would feel the same thing that you felt." (25:25)
> Y: "You know migraines? It's like you have a brief pain that came out of nowhere and it just, oh it hurt, then before you even finish that sentence, it stopped hurting" (25:30).

Animation 3 evoked the same feeling as "when you're running" (Y, 41:00). Asked how that feels in the body, Y did not know the language to describe it, but her "legs fe[lt] tired just looking at it" (Y, 47:30).

Finally, R, when asked about their model after watching animation three: "It just felt like a sphere" (24:37).

Transmodal qualities and the emergence of intuitive semiotic systems

As participants viewed the four animations, they used clay to develop and modulate their processes of intuitive semiotic representation. Along with the language used to directly or indirectly describe the felt dimension of experience, participants' manipulation of the clay often reflected the transmodal qualities of the observed kinematic phenomena. These transmodal qualities were then used to inform, in real-time, the participants' modeling approaches: they served as a source of pre-symbolic sense-making to draw from in the process of semiotic structuring. Often, participants referred to features of earlier models when constructing novel ones, creating emergent, consistent semiotic *systems* of representation of the observed phenomena. The representations were intuitive, in that they did not refer to or resemble the formal systems or structures modeling kinematic representation common in Western education–namely graphs (DiSessa et al., 1991).

Consistently, participants were observed rolling the clay rapidly (R, 9:30, 11:25; V, 13:30, 17:30; K, 14:37; Y, 33:49), tossing the clay from hand to hand (M, 18:56), or squeezing the clay (M, 18:42; R, 11:07, 19:00) while, or directly after watching the animations of acceleration. However, at times participants held the clay still whilst watching the animation, and then immediately began shaping the clay once the animation finished (V, 22:10, 27:55).

In multiple models, there was a relationship between the quantity of clay used and the speed of the object on the screen, further suggesting transmodal qualities present in the participants' phenomenology.

K: "It never changes speed, so I made them the same size" (28:20)

In some models, less material corresponded to faster motion.

> V: "I think it should be flatter, since when it goes faster it starts getting a bit thinner. I feel like the flat represents that it was starting to go slow, and then it starts to get faster when the line gets thinner." (29:40, Model 2)

In other models, there was the opposite relationship:

D: "The size gets bigger as the ball gets faster" (19:30, Model 2)

Transitioning from Model 1 to Model 2, Participant K varied both the spacing between discrete clay objects and the quantity of clay to suggest an increasing rate of acceleration:

> K: "This one went faster, so instead of doing it like that, I just went like *zoom.* Let me fix it" [*takes off some clay from the model*]. (19:40, Model 2)

At times, the participants' models were incongruent with their internal experience as reported. For example, when Participant D began making Model 1, they first shaped arrows in the direction of movement (9:39). D commented, "It's weird," and switched to a model of spheres increasing in size. Asked about the switch, D replied:

> D: "I tried to make it look like it was going faster, so it got bigger. When I first started, I tried to put an arrow to make it seem like the ball was moving faster. I changed it, because it didn't seem right when I put it down, in my mind. It didn't come out as I thought it would be" (11:55)

Discussion

How might these results inform us as learning scientists, education designers, and educators? Let us first reflect on several unanticipated features of our participants' behavior and output during the above-reported interviews. We witnessed youth deeply immersed in scientific phenomena, their perceptual positionality consequently shifting from passive observer to expressive receptor: the participants as well as the clay in their hands were *moved by* the kinematic animation. This experiential immersion sensitized the participants to the felt dimension of their perceptual phenomenology, expressing their subjective experience with words, gesture, and clay-shaping. Participants' felt experiences were transmodally rich, exhibiting a transference of kinematic visuality to the tactile, vestibular, proprioceptive, audial, and—along with sensory modalities—the affective. These multimodal evocations nurtured an idiosyncratic plurality of symbolizations, even amounting to novel semiotic systems of representation across the models. Participants conversed with the malleable clay intimately, reciprocally, and emergently, incorporating the material's feedback in iteratively remodeling their tacit understanding of acceleration. As such, the clay served as more than a medium of expression—it was a medium of impression; the medium truly was the message, at least complicitly.

The Results section characterized the data according to a list of common observations. To synthesize these multiple facets of behavior into a cohesive whole, let us return to the primary research questions put forth earlier in this thesis. To remind the reader, the questions were as follows:

- What is the relationship between available expressive media and potential semiotic systems during conceptual learning?
- What is the pedagogical potential inherent in attending to the felt dimension of experience in learning?

Let us begin with the first question: the relationship between available media and semiotic systems of representation. Different media appear to have potentiated different semiotic systems. Not one participant used clay to model a graph nor to shape words, whereas markers were used to construct graphs and words. In contrast, not one participant used the markers themselves to form semiotic constructions. Moreover, perhaps in our philological scrutiny of medium–semiosis pairings we are missing a critical epistemic–pedagogical consideration, that of the source perceptual phenomenology actuating the expressivity. The question then becomes not one of whether all semiotic systems are created equally, but if all semiotic media afford equal

conceptual sense-making opportunities—and if not, whether the differences are significant or superficial (Kress, 2009). Are the particular material affordances of pencil-on-paper cognitively commensurate to those of clay-in-hand? How might this commensurateness relate to modal particularities of the to-be-expressed sensuous experience? Consider the transmodal expressivity demonstrated by the participants—the transference of kinematics to haptic-tactility and sound—as well as the affective relationship to materiality and to perceptual phenomena the youth exhibited. Do certain media lend themselves to sensory engagement that moves students closer to the felt dimension of their experience, while others—even, or perhaps precisely those that are exquisitely suitable for etching symbolic notations—risk implicitly forgoing students' access to the richness of their sensory experience in their processes of developing conceptual understanding?

In attempting to address our first research question, we have thus ended up with new questions. Through this line of investigation, this research invites us to consider what, indeed, are the pedagogically desirable features of *any* semiotic medium with respect to experiential stimulus, conceptual learning, and representation. Indeed, one limitation of this research project was the lack of a comparison to clay as an expressive medium, save marker on whiteboard. Even so, observations of participants' engagement with the clay do suggest certain material characteristics especially potent for contemplative, multimodal conceptual learning. For one, the durability of clay, and its ability to sustain imprints of haptic-tactile engagement, suggest the cognitive importance of tracing a trajectory of understanding via materiality that records the morphology of perceptual phenomenology. This turn from the ephemeral inner gesture to the concrete public record makes intuitive semiotic systems visible and extends their life, allowing for immersion, reflection, elaboration, refinement, and alteration—it grounds fleeting qualia into disciplinary discourse. Furthermore, this material durability affords public scrutiny of idiosyncratic expressive artifacts, thus inviting peer-collaboration and, hopefully, fostering a classroom epistemic climate (Feucht, 2010) of inclusivity, curiosity, and what Turkle and Papert (1991) call "epistemological pluralism." "Showing one's work" becomes untethered from the flatness of paper or screen, instead becoming graspable, moveable, moldable, shareable, feelable.

The second research question—concerning the pedagogical potential inherent in attending to the felt dimension of experience in learning—points towards the possibilities of a new paradigm for action-based embodied design of learning environments, one that emphasizes the multimodal nature of conceptual sense-making. That is to say, how might we consider educational design differently with a departure from the presupposition of any one semiotic representation and from a privileging of particular sensory modalities? Without pre-constraining the learning process according to a goal medium (e.g., paper) and a goal representation (e.g., graph) inscribed in a goal modality (visual), a wellspring of sensorially grounded, idiosyncratic creativity becomes recruited for students to draw from. Suddenly, activities such as clay-modeling appear less strange, less out of place, more welcoming of the multimodal kaleidoscope inherent in the unfolding process of conceptual formation.

This approach to pedagogy, unconstrained by prescriptive semiotic systems constructed for prescriptive sensory modalities, beckons forth an epistemic climate that welcomes a multiplicity of meaning-making. Teaching returns to the felt experience of the student,

suspending (even briefly) the assumption that there exists an ultimate path to conceptual understanding and to semiotic representation, and that the goal of education is to lead back students who have gone astray. This departure does not exclude or eliminate the consideration of how insight then becomes canonized in prevalent semiotic forms. Instead, disciplinary discourse retains a tether to phenomenology and a rootedness in lived experience. Without modalist and semiotic preconceptions, education design becomes free to ask: What experiences could—and indeed already do, in situated, lived contexts within and beyond the classroom—give rise to conceptual insight?

Indeed, as this research suggests, learners' conceptual formations do not subscribe to sensory monogamy: though the interview activity primarily worked in the haptic–tactile dimension, participants never faced transmodal mental blockage. Participants naturally transposed motive intensity, rhythm, and dynamism into shape, gesture, sound, while mentally transporting themselves to richly sensuous imagined environments associated with such motive qualities. Thus, we may wonder, what are the elements necessary to create a safe environment for students to cultivate an intimacy with their felt experience? What should students be encouraged, supported, and guided to do?

Again we have but raised new questions. First and foremost, this research has shown that slowness is of essence when supporting students in developing an intimacy with their felt experience. An insistence on speed runs antithetical to a contemplative approach to learning (even when the conceptual focus is acceleration!) Students should be given time to slip further into a sensitivity to the inner movements of their being and the rhythms and textures of their sense-making. This process should not be rushed. Key to this pedagogical spaciousness is the embrace of an epistemic attitude transcendent of right and wrong, and, critically, of the necessity of—or rush to—language. To put into words the subtleties and ephemeralities of our felt experience is a remarkably difficult endeavor, prone to stress and dissatisfaction for all interlocutors involved. This research suggests that to invite an attending to different aspects of the sensuous tapestry of experience, without enforcing an expectation for verbalization, enables students to dwell closer to a direct relationship with their sense-making, as it unfolds. As observed in the participants' behavior, there is potential in the classroom for students' awareness to shift from seeking to receiving. This beckons in an epistemic stance of engaged curiosity, of wonder, of awe, for the enigmatic marvels of multimodal sense-making. As this research demonstrates, to ask students, *What do you feel? What do you hear? What do you see? What do you imagine?* is to invite students into a non-judgemental and receptive relationship with themselves, their senses, their community, and their environment. Suddenly, acceleration can be lonely, spicy, thick or thin, a river leading into an ocean.

Future work

This thesis investigated the phenomenology of transmodal semiosis. As such, barring the provision of a specified phenomenon (kinematic trajectories) and a stipulated representational medium (clay), the methodology was deliberately geared to accommodate divergent semiotic production. As such, study participants were encouraged to signify their experience in any form that may come forth for them. Consequently, we witnessed a broad array of idiosyncratic

symbolic artifacts and semiotic systems. These productions stimulated conversations that lent us microgenetic insight into the sensuous grounding of disciplinary concepts. However, what this research did not explore is the potential canonization of insight into formal scientific semiotic systems. For example, how would Participant K signify their sequence of clay balls of increasing volume in the form of a table, a graph, or an algebraic formula? What, if any, are the tradeoffs of fostering semiotic divergence for assuring the minimal disciplinary conformity that a community of practice requires to coordinate their discourse? Future research could investigate how multimodal qualities of tacit understanding may support the assimilation of formal semiotic systems (cf. diSessa et al., 1991), examining in particular the role of semiotic media and facilitation methods in this progression. We would look to understand how we might support students in maintaining conceptual grounding of target content in multimodal enactment and plastic production, even as they couch these experiences in scientific language. What is lost, what is gained, and how do we negotiate the enactive–symbolic epistemic divide?

Furthermore, there is opportunity to complement the qualitative data gathered in this research with multimodal quantitative analysis. Recurrent behavior analysis approaches (such as Recurrence Quantification Analysis) that aggregates multimodal data (e.g., gaze tracking and haptic sensing) could be used to elucidate patterns and phases of multimodal interactivity in relationship to the progression of conceptual understanding (Tancredi et al., 2021). Findings from this analysis could inform novel approaches to educational design that facilitate "bridging practices" between contemplative-somatic insight and canonized semiotic representation (Morgan & Abrahamson, 2016, 2018).

Finally, there exists a world of possibility for extending this research into the space of new media. As education moves ever further into the digital realm, it is imperative for students and teachers not to lose contact with their sensory experience (Abrahamson et al., in press, 2021; Penny, 2022). The vague fog that creeps over our perceptual phenomenology after long hours on video-conference applications is becoming all too familiar. Future work would do well to explore designs for *multimodal contemplative learning in digital spaces*—scalable and accessible design that cultivates a slow, diligent attentiveness to the unfolding of subjective experience (Höök, 2018). Indeed, future work may look beyond the screen towards novel forms of tangible user interfaces that are polymorphic and actuated, enabling haptic-tactile communication and collaboration. This direction holds the potential to invite in a new research paradigm for manipulatives in STEM education: moving from out-of-hand, to making-with, and ultimately to experiencing-through.

Conclusion

This thesis has explored the relationship between available expressive media and potential semiotic systems during conceptual learning, as well as the pedagogical potential inherent in attending to the felt dimension of experience in learning. The study's findings have highlighted the importance of considering the material characteristics of expressive media and their potential to afford rich sensory engagement, which can support students in grounding conceptual understanding in their perceptual phenomenology. The study has also demonstrated the importance of attending to the felt dimension of experience in learning and how it can nurture a

plurality of idiosyncratic symbolizations, resulting in multimodal semiotic systems of representation.

Furthermore, this research invites us to consider the pedagogical implications of semiotic media with respect to experiential stimuli and conceptual representation. This points towards the possibilities of a new paradigm for action-based embodied design of learning environments that emphasizes the multimodal nature of conceptual sense-making, from learning out-of-hand, to making-with, and ultimately to experiencing-through. By departing from the presupposition of any one semiotic representation and from a privileging of particular sensory modalities, this approach to pedagogy can foster a classroom epistemic climate of inclusivity, curiosity, and epistemological pluralism. Thus, this study provides a foundation for further research and development of pedagogical approaches that integrate sensory engagement and multimodal expression, empowering students to engage deeply, with their whole being, in a radically participatory praxis of sense-making in STEAM learning.

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Appendix A

Definition of Keywords

Keyword	Definition	Example
Modality	Sensorimotor system	Visual, auditory, tactile, body-in-space, balance, manual, oral, whole-body movements
Sensuous	Involving one or more sensorimotor modalities	Situations that include any of the above characteristics
Multimodal	Involving multiple sensorimotor modalities	Visual-auditory, tactile-proprioceptive
Transmodal submodality	Qualities that exist in multiple modalities	Intensity, rhythm, duration

Appendix B

Semi-supervised Clinical Interview Protocol

What we say/do	Why we we say/do it	Possible Responses	How to respond to those responses
Hi, I'm from the University of California at Berkeley. First of all, thanks for agreeing to take part in this study. I'd like to get your help to understand how students think about stuff. As part of my work, I design activities for learning. I use computers and all kinds of other technology. It's really important to meet and talk with students as I develop this technology, to provide me with feedback. Today I'm going to be asking you some questions and working with some activities, but remember there are no right or wrong answers. I just want to hear what you have to say about these things. I'll be glad to answer any questions you have now or later.	Introduce ourselves.	I know someone at Cal – do you know them?	Very cool, Cal has a lot of awesome people there. It's a big community!
How old are you? What grade are you in?	Document age and grade	I'm 8, in 2nd grade!	Oh wow cool, second grade is so much fun.

You'll notice we're using a camera to video-tape this session. We use it because we don't want to miss anything you say. If at anytime you wish not to be recorded, please let us know and we'll turn off the camera.	Make students comfortable; Let them understand their rights as volunteer participants.	How many people are going to watch this?	I won't share this publicly, but other professors and and researchers like me will watch it – maybe even in other countries.
[*bring out balls of clay of different colors]* We're going to start just playing with some clay. Do you like clay? Have you made things with clay before?	Introduce materials	Yes, I love clay! I made a dragon in art class No I don't like clay, its gross	Great! Clay can be used for so many things Imagine that the clay is like any other object - maybe like a stone on the ground that you can change into different shapes. Also, we can wash our hands at the end.
Please take a ball of clay in your hands. We're going to have our eyes closed for this short activity, just for the next few minutes. Is that okay with you?	Ensure comfort of having eyes closed, indicate length of activity	I'd rather keep them open	That's fine too! If you want to try with your eyes closed at first or maybe a little later, I encourage it
We're going to take some breaths together. Nothing too long, just how we normally breathe. But I want you to do something with the clay each time you breathe in. Maybe you squeeze it, maybe you roll it in your hand, maybe you pinch it. [*take 5-10 breaths]*	Get connected to the clay, dropping into less conceptual space, feel comfortable with abstract, personal expression with the clay	Why are we doing this?	This is a way to get to know the clay – you know, like having a conversation with it, like making a new friend

Nice! Now, I want you to keep doing that, but also doing something different the you breathe out. [*take another 5-10 breaths]* [spend 3-5 minutes in this stage, really setting up the affective space]			
Nice, you can let that go now, but keep your eyes closed please. Now, I want to hear a little bit more about how the experience with the clay feels. I want you to share with me some physical descriptions, like "squishy". But I want you to take a long breath in between each description. So it will look like, *breath in, breath out, "*warm" Does that make sense? Let's do this for just a little while. *Get 3 physical descriptions.* Really nice. Now, can you share with me some feeling descriptions, about how you feel? Maybe you	turn one's attention from *what* to *how*	Not really… How many descriptions do you want?	*Demonstrate again.* No specific number, if you feel like there's nothing to add we can stop, otherwise I will stop you after a little while

feel relaxed, nervous, confused, curious. *Get 1-3 feeling descriptions.* Awesome! Finally, are there any images, words, sounds, that are in your mind and that you want to share? *Get 1-3 mental descriptions.*			
Great, that was fantastic. Now, in a moment we will open our eyes. Before that, I want to invite you to play with exploring, what might it feel like if the clay were equally moving your fingers and hand as much as you were moving it. There's no right or wrong answer here, and maybe it makes no sense. Don't think about it, just invite that in.	Go down through the different strata of the experience (beneath the discursive, sensorial, and emotional) by adopting a specific 'attention position'	That makes no sense at all	That's fine! What would happen if you imagined that you were the clay? Would you feel like any part of you were pushing back?
Really nice! You can open your eyes now, but keep some of your attention on the clay if you can.			

Ok, I'm going to bring up a few scenarios, and ask a few questions. Again, I'm not looking for any right or wrong answer. I'm curious to see how you use your clay to help you make sense of these questions.			
[*pull up acceleration sketch #1]* In this scenario, we have a little dot.. Can you tell me what about this dot is changing?	Start to direct attention towards acceleration (not only distance is changing, but also distance over time)	Where the bird is?	Yes, that's definitely true, the dot is moving! Is there anything else changing?
Once they name that the amount of distance moved per time is changing Nice. Now say you had to model what you were seeing using the clay, and then leave your model here to come back to tomorrow, how would you do this? In other words, if all you have is clay, and you want to communicate to someone else what you just saw, how would you do this? You're not allowed to make letters and words… And I'm mainly interested in how you capture this change.	Prompting for semiotic means of objectification – the stabilizing of intuitive imagery in time	This makes no sense at all.	That's okay! I'm most interested in how you might use the clay to capture the change you are seeing. First, you can ask yourself, "how does this change feel in my body?" And then maybe put that into the clay.

So what did you do with the clay? Why'd you do that?	Vocal self-reflection on why they did what they did with the clay	Well I made the clay fat at first and then thinner and thinner	Cool! Why'd you do that?
Ok, here's another scenario. [*pull up acceleration #2 - accelerating faster than #1]* Are there any any differences between the way this dot moves and the last?	Work towards building a comparative understanding of the observed phenomenon		
Take another piece of clay, and again try to model what you see for someone else to pick up later.	Prompting for semiotic means of objectification – the stabilizing of intuitive imagery in time		
What did you make? Why?	Vocal self-reflection on why they did what they did with the clay		
How would you compare your first clay model to your second?	Highlight the qualitative differences between these two instances of the phenomenon (and the quantitative differences these stem from).		
[*bring up acceleration #3 - slowing down]*			

Same thing here. Can you communicate what you're seeing using the clay? How about with paper?			
How does this one differ from the other two?			
[*bring up acceleration #4 - no acceleration]*			
Ok, here's our last scenario. How would you communicate this? The goal is that if someone were to come into the room later and see your four clay models, they could more-or-less understand what you were seeing earlier. What might that look like?	Interesting edge case – no change in speed at all. How does this fit into their semiotic paradigm?		
How does this one differ from the others? Why?			
Now, here's some paper. How would you draw these four scenarios so that someone could come tomorrow and understand what you saw?	Explore transmodal expression of felt experience, working towards grounding intuitive understanding in more formalized semiotic means of objectifying		
Ok, we can put the clay down, and the birds. What was that like for you?			
Did any of this remind you of anything else,			

maybe something you've felt or seen before?			

Appendix C

Source Code for Acceleration Animations in P5.js

```
let pos;

let velocity = 1;
let acceleration;
let mode = 0;

function setup() {
  createCanvas(window.innerWidth, window.innerHeight);
  background(0);
}

function setup1() {
  velocity = 1;
  acceleration = 1.01;
  mode = 1;
}

function setup2() {
  velocity = 1;
  acceleration = 1.04;
  mode = 2;
}

function setup3() {
  velocity = 10;
  acceleration = .995;
  mode = 3;
}
function setup4() {
  velocity = 4;
  acceleration = 1;
  mode = 4;
}

function draw() {
   background(0);

   fill(255);
```

```
    noStroke();

   if(!mode) return;

    push();
    translate(pos.x, pos.y);
    circle(0,0,25)

    if(pos.x > width + 100) {

    }

    else {
      pos.x += velocity;
      velocity = velocity * acceleration;
    }
}

function mousePressed() {
   fullscreen(true);
   createCanvas(window.innerWidth, window.innerHeight);
   pos = createVector(0, height/2);

  switch(mode){
      case 1:
            setup1();
            break;
      case 2:
            setup2();
            break;
      case 3:
            setup3();
            break;
      case 4:
            setup4();
            break;
      }
}


function keyPressed() {
   createCanvas(window.innerWidth, window.innerHeight);
```

```
  pos = createVector(0, height/2);

  switch(key) {
    case '1':
      setup1();
      break;
    case '2':
      setup2();
      break;
    case '3':
      setup3();
      break;
    case '4':
      setup4();
      break;
  }
}
```