

Multidimensional Representations:

Designing Learning Materials That Facilitate Connections Between Conjugation and Resonance

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Project for EDUC 290C Design Based Research

Instructor: Dor Abrahamson

Objective: Connecting Concepts

To provide a method for undergraduate chemistry students to link and relate the concepts of resonance and conjugation.

Background: Visualizing the Invisible

Chemistry occurs at the sub-microscopic scale. Consequently, chemists have developed various types of external representations in order to visualize the miniscule structures and rationalize the reactivities of the substances that they study. Because external representations provide valuable insight into the invisible world of molecules, they are essential to the teaching and learning of chemistry.¹ One representation, a Lewis structure, is commonly used to depict the structure of a molecule by designating each atom with letters and the bonds between atoms as lines between the letters. In certain cases, multiple logical Lewis structures can be drawn to illustrate a single molecule by “pushing” the bonds back and forth between different sets of atoms. In such a case, it is the superposition of all Lewis structures that embodies the true structure of the molecule.

This composite representation is known as resonance. Although resonance is introduced as a simple way to describe structure, the student eventually finds that it is also an indicator of electron delocalization in a molecule, which in turn affects its reactivity and chemical behavior. Despite its usefulness, many students struggle to understand resonance and to identify when resonance occurs.^{2–4} Many educators have proposed ways to tackle this issue; examples include visual demonstrations,⁵ unique analogies,⁴ and a call to replace the word “resonance” with alternative terminology.³ However, Mullins suggests resonance, and other electron delocalization models in general, could be better understood by “placing them in context [with each other].”⁶ Conjugation, another model used to express electron delocalization, occurs when at least three p-orbitals on adjacent atoms are aligned. Due to the proximity and alignment of the orbitals, electrons are able to travel through the whole “conjugated system.” However, unlike Lewis structures and resonance, which emphasize a 2D perspective of the molecule, conjugation requires the consideration of the 3D spatial orientation of the atoms, bonds, and p-orbitals, which is not explicitly shown in a Lewis structure. Furthermore, it has been shown that another stumbling block encountered by students in chemistry is the translation between different diagrammatic representations.¹ Thus, it could be hypothesized that the direct conversion between Lewis structures and a 3D depiction might in itself be a barrier to relating these concepts.

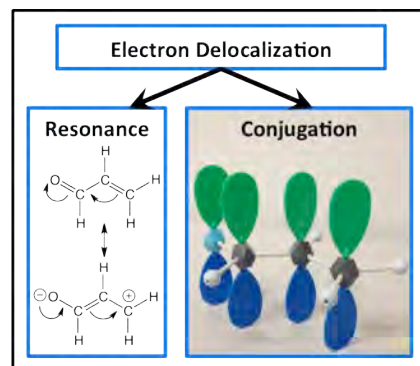


Figure 1. Models of electron delocalization.

Design: Adding an Extra Dimension

In order to facilitate the conversion from one representation to the other, and in doing so better relate resonance and conjugation, a hybrid representation of the two has been developed. To bring a 3D quality to Lewis structures while engaging in a discussion about conjugation and resonance, a kit was assembled that included a stainless steel “whiteboard,” dry-erase markers, and magnetic pieces representing a single lobe of a p-orbital. The familiar Lewis structures could be drawn on the board, and then the magnetic pieces placed over the appropriate atoms to simulate the extra dimensionality necessary to identify conjugation. The reflective quality of the board allowed the other half of the p-orbital to manifest.

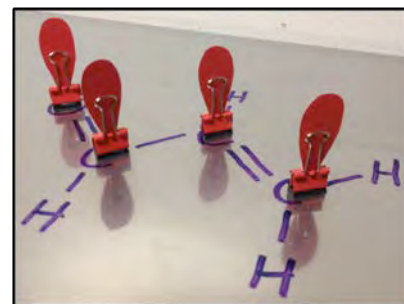


Figure 2. Demonstration of the kit in use.

Findings

Interviews with organic chemistry students currently enrolled in Chem 3A are presently being scheduled but have not yet commenced.

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Process and Object in Constructing Material Models of Polynomial Factorization

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Objective: Apply and Expand Sfard's Process/Object Duality of Mathematical Concepts

The objective of this design-based research project was to apply and expand Sfard's object/process ontological framework of mathematical understanding within the context of polynomial factorization.

Background and Research Problem: Sfard's Process/Product Conceptual Duality

Sfard (1987, 1991, 1995) has put forth an ontological framework, by which mathematical concepts are process–object dualities. This research study attempted to expand Sfard's ontological framework into a theory of cognition. I hypothesized that Sfard's ontology is applicable not only to mathematical concepts per se, but also to the process of problem solving. I evaluated my hypothesis by investigating the process of problem solving in the domain of polynomial factorization. To begin with, I had to design appropriate instructional materials and implicate their process/object duality per Sfard's framework.

Design: Using Algebra Tiles to Model Process/Object in Polynomial Factorization

With a variant on Algebra Tiles, I built a set of materials comprising 2 red squares, 5 yellow rectangles, and 3 green squares.

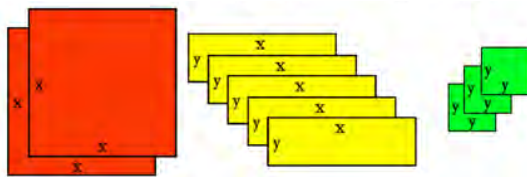


Methods

In this explorative pilot study, I interviewed one graduate-level student. The videotape was transcribed and micro-analyzed. Using Sfard's duality, I coded the transcription to identify and sort utterances as implicating either process or object.

Findings

- (a) The rectangular elements given to the interviewee are structures (objects). Calculating the sum of their areas is a process.

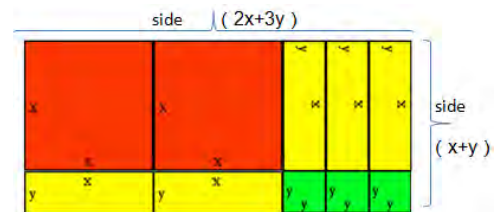


For example, as in the figure on the left, the two red rectangles (objects) relate to a calculation of areas $2x^2$ (a process). Similarly, we can convert between objects and processes in the yellow and green shapes, to $5xy$ and $3y^2$ respectively. The main process here is that of addition to obtain the total area of the parts ($2x^2 + 5xy + 3y^2$). In this way, the algebraic expression can be seen both as a process (addition) and an object (a collection of squares).

- (b) The combined rectangle and its sides are structures (objects). The calculation of the total area is a process.

In the figure on the right, each side corresponds to an algebraic expression ($x+y$ and $2x+3y$). The calculation of the total area $(2x+3y)(x+y)$ by way of multiplication is a process.

- (c) As a whole, the conversion between the expressions $2x^2 + 5xy + 3y^2$ and $(2x+3y)(x+y)$ is a process.



Conclusion

In accord with my hypothesis, analysis of a participant's transcribed interaction with the designed materials demonstrated that Sfard's ontology obtains in the case of problem solving. In a future study, I will consider the implications of these findings for mathematics education. Could students benefit from acknowledging Sfard's duality in their own reasoning?

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Easy Equilibrium – Self Discovery in Chem1A

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Objective: Creating an Evolution of Thought

This design focuses on Easy Equilibrium's (EE) design effectiveness at addressing difficulties in understanding equilibrium for students in UC Berkeley's introductory chemistry course, Chem1A. Equilibrium is a fundamental topic in chemistry, and just as algebra is the gateway to understanding complex mathematics, equilibrium is the gateway to understanding many processes in the natural sciences. The design presents itself as an alternative method to teach the concept in a more efficient manner by exposing students to many modalities in a progressive format that fosters a phenomenological evolution of thought.

Background: "Teaching Science is the Process of Telling Smaller and Smaller Lies"

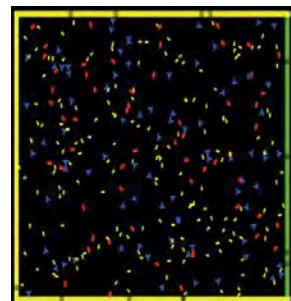
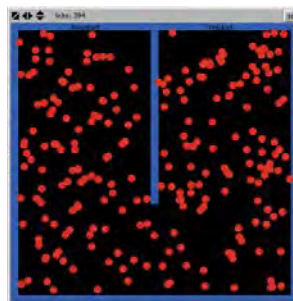
The problem in understanding equilibrium is that students have a formalistic curriculum about a complex phenomenon – a bidirectional, dynamic, and simultaneous processes. During my Fall 2010 semester in Chem1A lab, a substitute theoretical chemist GSI commented, "Teaching science is the process of telling smaller and smaller lies". Throughout basic chemistry education, students are repetitively taught that reactions proceed in one direction—equilibrium defies this logic. Upon learning about equilibrium, many students have difficulties breaking down the formalisms that they have been taught, as the concept is only as real and adaptable to them as numbers are on a paper; as a result, they are unable to make the logical leap to understand the reversibility of chemical equations. According to Nathan (2012), "formalisms are confined to specialized representational forms that use heavily regulated notational systems with no inherent meaning except those that are established by convention to convey concepts and relations with a high degree of specificity." The Chem1A curriculum as it stands does not afford novice chemists to explore chemistry in multiple modalities, and without dialogue or a qualitative foundation to understanding equilibrium, students have difficulties in developing a representational understanding for the analytical problems that they are first presented with.

Design: Progressive Bridging Analogies



The goal of EE is for students first to develop an understanding, beyond ratios on paper, that is honest to the equilibrium phenomenon, before they progress toward more difficult concepts. Becvar et al. (2005) maintain that representations "operate as instantiations of essential spatiodynamic features that are not efficiently conveyed in other modalities...and as such, are vital resources for shaping theoretical understandings in collaborative, face-to-face scientific activity." The dynamicism of EE is designed to introduce the complexity underlying equilibrium. Using *NetLogo* (Wilensky, 1999), I built two simulations of equilibrium. I also built a physical model with water and dye as a *bridging analogy* into the *NetLogo* model (Clement, 1993). This

physical-virtual design was further inspired by the *bifocal modeling* design framework (Blikstein & Wilensky, 2007).



Findings

As students progressed through the three models, they evolved a sophisticated understanding of equilibrium. The juxtaposition of the three models brought forth understanding about Brownian motion of particles when a reaction is said to be at equilibrium. Students' view of a naïve, homeostatic equilibrium was perturbed as the virtual models of quantitative movement gave a more precise understanding of concentration gradients and reaction rates. The virtual models provided a simplified, mediated view that students trusted after experiencing the honesty of the physical model. The Easy Equilibrium design illustrated the dynamics of equilibrium by allowing users to visualize the qualitative, quantitative, and quintessential meaning of the ratios K and Q .

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Exploring Boundary Crossing in an Interdisciplinary Team

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Objective: To Explore the Process of Boundary Crossing in Interdisciplinary Projects

Interdisciplinary teams working together on a project, such as in global health programs, must constantly negotiate individual and group goals. Understanding how this process unfolds could help in planning and implementing these projects. By focusing on central objects that mediate the team's activity, rather than only individual aspects of each team member, one could gain new forms of insight into the group's dynamics and thus into their optimal collaboration practice.

Background: Interdisciplinary Teams Interact as Complex Systems Around Boundary Objects

In the field of global health, the majority of project teams are composed of stakeholders coming from a variety of backgrounds. While the team acts with an overarching goal of completing a project, individuals' competing goals and constraints impact how they negotiate collaboration. Interdisciplinary teams are thus complex adaptive systems, "a collection of individual agents with freedom to act in ways that are not always totally predictable, and whose actions are interconnected so that one agent's actions changes the context for other agents" (Plsek & Greenhalgh, 2011).

The theory of boundary objects and boundary crossings (Akkerman & Bakker, 2011; Star & Griesemer, 1989) offers tools for conducting systemic analysis of team negotiations. Boundary objects are ontologies (e.g., an artifact) that indirectly liaise efforts of unrelated parties; boundary crossings are practices by which these unrelated parties engage this common ontology. Such analysis foregrounds team dynamics by which they negotiate across a boundary object.

Design: Creating a Board Game to Simulate Group Dynamics Related to Boundary Crossing

To support and investigate the dynamics of heterogeneous-group projects, I built a simulation game. It consists of a set of blocks, a ruler, and an 8"x8" sheet of paper (as the base for a structure; Fig. 1). The overall rules for the team are that the structure must be 12" tall and touch all four sides of the paper.

Each player is given 2-3 rules. Each player can only use the affordances of the blocks as defined by her assigned rules. In the 1st round, each player is only privy to her set of rules, whereas in the 2nd round they are allowed to discuss their rules as they collectively build the structure. This game could potentially help a *specific team* to better understand its dynamics, even as it may offer *researchers* opportunities to investigate collaborative learning mechanisms.

My study was designed to address the following research questions: How does boundary crossing occur when players do or do not share their individual rules? Do these conditions result in different personal and/or collective achievement or different cooperation patterns? How do players organize the rules once they are revealed? To address the questions, I ran a set of pilot trials, then closely analyzed videotapes of these trials.

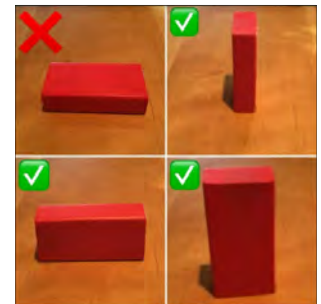


Fig. 1: (Clockwise): Game materials; one player's rule set; participants negotiating the use of blocks.

Results and Conclusions

Initial game trials with 2 groups, each composed of 2-3 players, confirm that it bears the potential of offering players pathways to productive collaboration while offering researchers insight into the social dynamics of boundary crossing within interdisciplinary teams. Further refinement of the rules could help researchers better elucidate more nuanced interactions between participants. Future research would engage multiple participants in playing the game with additional rounds, vary the sets of rules, and use multi-dimensional materials to complexify the task.

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Giant Steps for Algebra

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Objectives: Algebra Metaphors and Learning

This design-based research project investigated alternative cognitive foundations for algebraic reasoning. The initial impetus for the design was a conjecture associating students' poor understanding of algebra content with the pervasive metaphor underlying their conceptualization of algebraic equations (Vlassis, 2002). Building on Dickinson and Eade (2004), the design instantiated algebraic expressions (e.g., $2x + 1 = 3x - 2$), which are traditionally visualized as two distinct sets of discrete quantities balanced across a scale, as two distinct journeys an agent takes to traverse a single continuous linear interval.

Design Problem and Process

In arithmetic thinking the “=” sign is conceptualized operationally (Carpenter, Franke, & Levi, 2003). This conceptualization of the “=” sign is absent of a relational sense, (Jones et al., 2012)—a sense that is pivotal for conventional treatment of algebraic equations. Using a story metaphor to ground concepts, the design seeks to offer a more nuanced and relational interpretation of the = sign.

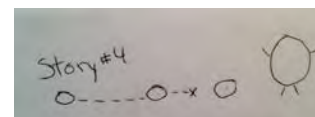
The physical design consists of a sand tray with small marbles buried in the sand. There were six stories that described the process by which the ‘treasures’ were buried. The relationship between two different trips revealed the length of the variable (giants steps) in inches and thus the location of the treasure. There were three conditions based on the different problem-solving tools provided (paper and pencil, pushpins and corkboard, elastic ruler and fixed inch markers).

Design Discoveries



The researcher engaged in micro-ethnographic qualitative analysis. The analyses focused on the three experimental conditions and the extent to which the tools obfuscated or illuminated the phenomena. Transparency emerged as a pivotal construct highlighting this design's opportunities and challenges and how aspects of the design enabled participants to “see” phenomena through their models. The

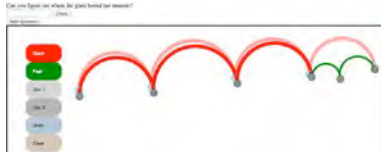
analyses revealed the importance of spatially aligning the two journeys such that the relationship between the variable and integer could be identified. This critical coordination was facilitated by the participants' use of their models as a method for visualizing the two separate journeys as overlaid, almost as if these occurred simultaneously. Through this action participants were able to see that two sides of the equation as co-indexical of the equations' identity, and the location of the treasure.



Conclusions

The construct of transparency illuminated the relations between learner, task, artifact, and content. We argue that the design restructured the solution of unknown-value problems as centered on manual coordination of situated quantities. And yet participants' accomplishment of these conceptually critical coordinations was predicated on the subjective transparency of relevant perceptual elements within the media. We thus corroborate and expand on constructivist critiques of modeling: What you do not build, you may not see.

Technology-Based Redesign



As we consider improvements to the Giant Steps for Algebra design, we have begun to develop a technology-based interface analogous to the concrete instantiations. Considerations for development include previous research indicating “computer manipulatives can help students build on their physical experiences, tying them tightly to symbolic representations” (Clements & Sarama, 2009, p. 148). Digital media afford

programmable display elements that could include stretch/shrink equipartitioned rulers, for example. However, our findings suggest that automatized transformation might remain opaque to the learner. As we continue to develop the computer-based version of Giant Steps of Algebra, we will carefully determine criteria for assessing whether the learner is ready to shift gears from manual to automatic with respect to each programmable element. For example, once the learner has demonstrated proficiency in building journeys with equal steps, the interaction mode will change so as to enable scaling with uniform units.

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“Read, Baby, Read!”: Embodied Rhythmic Synchrony in Special Needs Classrooms

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Objective: To Supplement Special-Needs Instructional Practices with Rhythm-Based Routines

Transitioning between activities can be time-consuming and difficult, especially for special-education classrooms, where students have a variety of complex needs. This design-based research project consisted of creating a transition song for a classroom of students with complex needs and evaluating its impact by tracking for changes over 4 weeks.

Background: Embodied Rhythmic Synchrony and Transitioning

Periodicity—the quality of an event recurring at fixed temporal intervals—characterizes human experience pervasively. Rhythmic physiological sensations pace one’s subjective experiences (Edensor, 2010), so that all sensing and sense-making are necessarily, if implicitly, mediated by rhythm (Duffy et al., 2011). Pulse and rhythm can provide a social collective a shared sense of time, where different individuals all embody a common temporal organization, allowing for coordination, attunement, and joint action in enacting cultural practices such as conversation, physical labor, athletic events, or musical performances. Deliberate interpersonal rhythmic actions, for example in a drum circle, purport a sense of self-awareness of affecting and being affected in the social collective.

One cultural practice that concerting could benefit is transitioning between activities. How could transitioning assume rhythmic form? Some mainstream classrooms use songs to assist the transition process, particularly into unfavorable activities, such as “clean up” or disciplined walking between locations. These transition songs foster a shared sense of belonging to the classroom group, as students coordinate their movements in accord with the rhythm they themselves generate. Furthermore, these songs provide a fixed and finite duration for task completion, thus increasing efficiency.

Design: A Rhythmical Transition song

The design came to fruition in collaboration with a special-needs teacher. The classroom was located in a public school in the East Bay, CA, and consisted of 8-9 children, aged 5-7, with a range of complex needs.

I redesigned an existing polyrhythmic chant, the legendary educator Harriett J. Ball’s classic “Read, baby, read!,” by simplifying its lyrics and structure. In Week 1, the teacher and I taught the song

to the class using a recorded track. Over Weeks 2 – 4, I accompanied the song on the ukulele to increase its conviviality. The students displayed excitement and enthusiasm towards interacting with the musical instrument, voluntarily taking turns to strum and tap it. Their individual relations to the music thus self-organized spontaneously as a group endeavor.

Microanalysis of video data demonstrated that all the students eventually found their own way, given their diverse neuro-motoric constitution, of expressing rhythm in vocalization and gesture as they signed, waved, clapped, and rocked in synchrony with the song’s beat. In a post-intervention interview, the teacher and support staff described the song as effecting “significant difference” in its power to “focus attention” during transition to, *and through* the reading session. They found that the song’s simple melody (it spans a mere tetrachord) and lyrics as well as its short duration enabled many students to master it and thus incentivized multiple concerted repetitions.



Figure 1: The teacher (on left) and I introduce the classroom to “Read, baby, read!” using sign language gesture (left); the students listen intently (right).

Conclusions

The field of cognitive science is increasingly drawn to the cultural phenomenon of socially organized rhythmic activities, whose qualities have been cited as bearing values for psycho-physiological regulation and interpersonal concerting. Transition songs such as “Read, baby, read!” are multimodal performance artifacts whose enactment brings forth these values for the benefit of all participants. For researchers and practitioners particularly in special education, such musical resources could stimulate an investigation focus on multifarious facets of teaching and learning, including problems of socialization, identity, and classroom climate, which are germane to all institutional settings. Future research will turn to subtler yet pervasive values rhythmic forms could bring to educational activities.

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Dynamic Social Mirrors: Social Technology-Based Supports for Collaboration

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Objective: Providing Data Rich Feedback to Improve Collaboration

In a hot, flat world, collaboration skills are critical for the life of participatory democracies. Yet collaboration is a dynamic process and evaluation of personal performance is based on data that is radically evanescent. With an aim to support collaboration, what information can help people identify and modify patterns in their interactions with others?

Background: Dynamic Social Mirrors - Augmented Feedback for Awareness and Goal Setting

In line with dynamic systems theory (Kelso, 2012), learners are conceived as searching for stable, functional coordinative structures (Schmidt & Fitzpatrick, 1996; Turvey, 1990) that allow for successful action–perception pairings in the context of a task and environment. Coordinative structures are built up over time and are discovered through use of one or more search processes occurring in response to task-based and environment-based constraints. These search processes comprise one way in which an organism, task, and environment can be said to be interdependent (Ashby, 1963), and coupled (Glassman, 1973). Within such a framework, one goal of learning design is to help learners narrow the search space for effective activity assemblies that serve as functional solutions to the given task–environment pairing. Knowledge of results (KR) and concurrent feedback (CFB) are two approaches to providing augmented feedback and narrowing learners' search for such coordinative structures. Relying on past research into dynamic visualization of collaborative processes, the current project has led to design, development, and testing of a dynamic social mirror that provides participants with visualizations of their talk during a collaborative problem solving game created at LRNG-GlassLab.

Design: Hybrid Concurrent Feedback and Knowledge of Results

Dynamic social mirrors stand to provide information about patterns in collaborators' talk, making evanescent data about their collaboration available for review and reflection—providing a basis for goal setting and behavior change. In the current project, I designed a digital, dynamic social mirror that provides players in a collaborative problem solving game with concurrent feedback about their talk as it occurs (see Figure 1, left). The social mirror updates every 0.01s, displaying which member of the collaboration is talking, the volume at which they are talking, the duration of their utterances, the duration of their silences, and the relation of key game events to their talk. The visualization is modelled after work by Chapple (1949) and Jaffe (1968). In playtests in Grades 4 – 10, the visualizations have been accessible, support identification of patterns in talk, and provide a basis for goal setting. Because the social mirrors are printable, they also function as KR style feedback (see Figure 1, right). Collaborators are able to compare visualizations—before and after goal setting—to evaluate performance against their goals.



Figure 1: On right: A printout of the social mirror from a game session. The digital version of the social mirror dynamically updates within the collaborative problem solving game created as a part of this project – ‘Deep Sea Crisis’. On right: Players are able to print the output of their conversation clock as the basis for identification and reflection on patterns in their communication.

Conclusions

The social mirror is viewed as one form of visualization, displaying one type of content—patterns in talk. It is expected that a range of alternative visualizations displaying alternative content are imaginable and worth pursuing. Work is now underway to develop an approach to visualizing the content of players talk. For more information, see www.challenge-21c.org

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The Specifications Game: Developing Mathematical Practices of Defining

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Objective: Foster, Investigate, and Model the Mathematical Practices of Defining

Defining, a central practice in mathematics, is different from its daily practice. Whereas students may know many mathematical definitions, these are often presented as fact. Consequently, students often have trouble formulating definitions, interpreting new definitions, and using definitions in proof and problem solving (Vinner, 1991). The rationale of the design project is that students may spontaneously engage in generating mathematical definitions as their pragmatic solution to a problem involving specificity of information, such as in responding to a problem of ambiguity.

Background

Commognitive Interpretive Framework. Mathematics learning can be modeled as the process of internalizing mathematical discourse (Sfard, 2007). The Specifications Game (SG) is designed to create an engaging context that generates the type of mathematical discourse often involved with the formulation of definitions.

Developing Mathematical Definitions. Mathematical definitions, I submit, are not inherent truisms but rather meaning-relations built to fulfill particular purposes, often via an iterative process of formulating and evaluating a definition with respect to its utility, conformity to intuition, or other criteria. A definition, I further submit, could be viewed as an *epistemic form* (a target structure guiding inquiry), the end product of an *epistemic game* (Collins & Ferguson, 1993). SG was designed to prompt students to reinvent one such epistemic game. SG draws on familiar cultural practices, sets up mathematical language as a potential solution to ambiguity, distributes the process over two participants and a set of materials, and encourages reflection, mathematization, and the practice of defining.

Design: The Specifications Game

In SG, two participants take on the role of ‘specifier’ and ‘checker’, respectively. The specifier is provided with a game board out of which the ‘goal shape’ has been cut out (Figure 1, left). The checker is provided with the goal shape, as well as a set of shapes that share some properties with the goal shape (Figure 1, right) and some post-it notes on which to draw additional shapes. Both players have visual access to

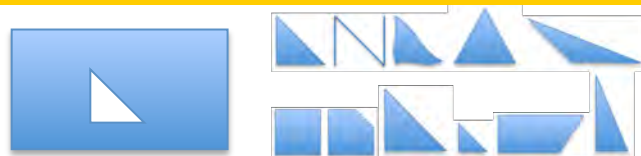


Figure 1: A game board (left) and associated game pieces (right).

the game board, but only the checker has visual access to the set of game pieces. During each turn, the specifier provides one specification describing his shape. The specifications may not include shape names nor refer to shapes that were previously used. During the checker’s turn, the checker provides the specifier with a shape that satisfies all specifications provided thus far. This shape may be selected from the set of game pieces or may be drawn on paper. If the shape does not fit the specifier’s board precisely, it is returned to the checker to be used again.

The specifier’s goal is to obtain the goal shape in as few turns as possible. The checker’s goal is to maximize the number of turns played. To this end, the checker tries to identify and provide shapes that, while satisfying all specifications given, are not the goal shape. When the specifier obtains the goal shape, the game ends.

Four dyads (ages 11 and 15, as well as pre-service teachers) participated in a pilot implementation of SG. Each dyad played the game at least twice, alternating roles. Next, I prompted them to: (a) examine and modify their list of requisite properties into a conjectured definition; (b) compare and evaluate alternative definitions for the same object; and (c) identify or generate definitions for unrelated mathematical concepts. All sessions were videotaped and then carefully micro-analyzed.

Conclusions

The practice of defining is developed via apprenticing into the field of mathematics. In this process, students move away from a view of mathematical definitions as arbitrary systems of constraints couched in non-normative language and disconnected from intuitive ways of thinking about the world, towards a view of definitions as epistemic forms satisfying specific properties that allow them to fulfill particular purposes. By distributing the defining process over two participants and a set of materials, SG supports students in enacting an epistemic game of formulating definitions. In this process and the subsequent guided reflection and mathematization, students become sensitized to properties of definitions such as specificity and minimality, resulting in a discursive shift away from mundane practices of defining.

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Promoting Equitable Access to Math Content through Collaborative Task Design

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Objective: Improve Access to Math Content by Regulating Small-Group Participation

Whereas collaborative activities have been shown to offer opportunities for learning (Boaler & Staples, 2008), productive collaboration is difficult to achieve (Barron, 2003). My goal was to design a collaborative task which promoted equitable participation by all group members through the use of specific design features, leading to equal opportunities to learn.

Background: Opportunities and Pitfalls of Collaborative Learning Activities

When implemented successfully, group learning activities foster conceptual development through the contesting, integration, and elaboration of knowledge among peers. Students' thinking is more likely to evolve when they explain, elaborate, and justify their mathematical beliefs to others (Brown & Palincsar, 1989; Schoenfeld, 2013). When unsuccessful, these activities can lead to missed learning opportunities for students, due to divide-and-conquer strategies or to the Status Differential Effect when a perceived high ability student takes control of a task (Abrahamson & Wilensky, 2005; Salomon & Globerson, 1989).

To elicit productive learning opportunities, researchers agree that collaborative tasks should be open-ended, accessible to all learners, require multiple skills, and promote positive interdependence (Cohen & Lotan, 2014; Johnson & Johnson, 1998). However, these task classifications are not design features themselves but rather desired outcomes of task design.

Design: Searching for Sequences, a Collaborative Algebra Task

I designed a collaborative Algebra task with the goal of promoting productive small-group interactions that enable equitable access to math content through the use of specific design features. *Searching for Sequences* covers content related to multiple representations of linear functions. The task requires groups to form four different 3-card pattern sequences using a set of 16 pattern cards distributed among group members. To assess the effects of specific design features on student participation, I designed two different versions of the task. *Version 1* uses color-coded pattern cards to restrict touch based on card color, thus fostering a free-play structure for students to play cards. *Version 2* uses white pattern cards that are dealt out like playing cards at the beginning of the task. Students hold the cards in their hands, shielding them from others' view, and take turns playing

cards. Thus we implemented restrictions either on individual touch (Version 1) or sight (Version 2) access so as to explore approaches to fostering ownership/control over a piece of the task. Both versions include four extra pattern cards; only 12 out of the 16 are needed to complete the sequences, creating multiple correct solutions and increased cognitive demand.



Figure 1: Students engaged in the *Searching for Sequences* task, *Version 1* (left) and *Version 2* (right)

Pilot-Study Findings and Conclusions

When implemented as intended, both the restricted touch with free-play (Version 1) and the restricted sight with turn taking (Version 2) were successful in achieving the intended goal of regulating participation among group members. However, turn-taking (Version 2) was easier for students to implement and enforce than restricted touch (Version 1). The playing board (Version 2) productively defined an accessible and shared workspace that was lacking in Version 1. Providing extra cards and allowing multiple solutions led to high cognitive demand with both versions. Future design iterations are underway.

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Rearview Mirrors for the “Expert Blind Spot”: Using Design to Access Surgeons’ Tacit Knowledge and Create Shared Referents for Teaching

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Objective: Helping Surgeons to be Better Teachers

To improve the teaching and learning of surgical skills in situations where some relevant perceptual information is obscured to the teacher and/or the student.

Background: Educating Students’ Attention

Learning a skill which requires manual dexterity is like learning to solve a class of problems with your body. Teachers can influence the process in several important ways: 1) they can define the bounds of the problems, 2) they can provide tools and strategies for solving the problems, and 3) they can provide feedback to improve performance. In order to perform these functions, teachers must be able to deconstruct movements (Bernstein, 1996; Dreyfus & Dreyfus, 1999), educate learners’ attention by parsing the skill (Churchill, 2011), and communicate effectively with students via multiple modalities (Becvar Weddle & Holland, 2010). Because surgical teachers are content experts but not necessarily pedagogical experts, they may suffer from “expert blind spot,” misconceptions about, or omissions from, what is important for learners to attend to at the initial stages of skill acquisition (Ball, 2000; Nathan et al, 2001). Providing an artifact that affords previously unavailable sensory information might help learners acquire the skill with “training wheels” while simultaneously stimulating teachers to reflect on available modes of perception and action. The result is improved shared understanding of an expanded “field of promoted action” (Reed & Bril, 1996).

Design: Seeing Under the Dissection

I created an artifact that allows surgeons and learners to see what is underneath or behind a vascular dissection. When used simultaneously by a teacher and a student, the design affords additional modes of sensory perception about the task (vision) while extending the physical field of promoted action to explicitly include the back wall of the vascular dissection. A clear, soft vinyl tray is stretched across the surface of a box containing a mirror, allowing for direct visualization of, and interaction with, the process of dissection from below via a mirror. A pork splenic vein dissection was used to simulate vascular dissection.



Figure 1: Vascular dissection apparatus.

Findings

I tested the design with an expert teacher and six novice medical students at the UCSF Surgical Skills Lab. Learners who most enthusiastically adopted the affordances of the apparatus itself were also the most fluent in describing their experiences while performing the dissection. In exploring the new artifact, attempting to discover its affordances, teachers and students were forced to consider what modes of perception were available—and important—to them. While designed to remove a barrier that normally forces surgeons to proceed based on proprioceptive and haptic feedback only, use of the artifact actually resulted in increased discussion of all types of feedback (visual, proprioceptive, and haptic).

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Puzzling Proofs

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Objective: Foreground Tacit Epistemic Practices for Proofs and Proving in Mathematics

Proofs and proving play central roles in mathematics. Yet when students engage in these practices, they struggle to move from process (proving) to product (proof). How might we reconceptualize instruction to support this transition?

Background: Proofs, Proving, and Mathematical Reasoning

Whereas the mathematical community requires primarily deductive proofs, these are only the final products of a very long process (CadwalladerOlsker, 2011). This process is experimental in nature and requires much tinkering: de/re-composing ideas; experimenting with ideas that fail; imagining intermediate steps; and even determining fragments of a proof that appear useful but whose role in the overall mosaic remains as yet under-defined.

These epistemic practices are not evident in how proof is taught or documented in textbooks. Over-emphasizing the product (proof) and the deductive reasoning it foregrounds is liable to deny students of opportunities to transition between abductive reasoning, often required in proving, and deductive/inductive reasoning invariably exemplified in proofs (Pedemonte, 2007).

Expert mathematicians often bring to bear implicit cognitive resources, such as spatial and directional metaphors, to help transitioning between a proof's process and product. However, by and large instructors are unaware of these tacit cognitive resources, and so they are liable to leave these resources as opaque to students.

Design: Proofs Like Puzzles

For the current project, I developed and piloted an activity for mathematical proving. The design took the form of a puzzle, with paper cards that featured either *steps of a proof* for the Pythagorean theorem, or *theorems and definitions* participants could use to justify and connect some of these steps. By identifying missing steps, exploring and justifying connections among the various parts of the proof, and eventually arranging the cards to produce a final proof, students were to experience some of the professional practices involved in proving theorems.

The cards were to act as material, cognitive, and epistemic resources that objectify knowledge in the form of intact elements of the mathematical problem-solving space, and as such to afford "interaction with knowledge" in ways that emulate interaction with material objects. Participants could cluster and arrange idea tokens they associate or view as sequential steps in a final proof, so that physical contiguity instantiates cognitive proximity. They could also re-arrange the tokens to explore alternative reasoning paths. These ongoing material and cognitive reconfigurations would emulate a generic design practice Schön (1992) dubs "see-move-see": Students could engineer a proving path (or parts thereof), evaluate it, recognize new potentials, and then redesign it accordingly. These actions would make individual students' work process and interim products publicly displayed for potential collaboration, thus evidencing the social component of expert mathematicians' professional practice of constructing and communicating proofs. The empirical component of my study consisted of evaluating my design.

Three undergraduate students participated in a task-based semi-structured interview (Ginsburg, 1997) that lasted approximately 90 minutes. The participants knew each other. They worked with one set of cards and multiple sticky cards, on which they took notes or added missing parts of the proof. I video-recorded the interview and photographed the activity board. I micro-analyzed the recorded data to build an account of how the various design features led to the behaviors I observed that were relevant to authentic engagement in mathematical proving (Abrahamson, 2009).

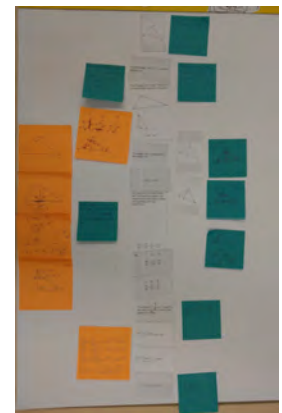


Fig. 1: Activity board with cards and notes.

Conclusions

Organizing math ideas as concrete tokens afforded social and physical interactions with cognitive resources that remain hidden in most proof-related classroom activities. These interactions shed light both on tacit social facets and diverse forms of reasoning occasioned in constructing and communicating proofs. Iterations of my design may support students in modifying their preconceptions of proofs/proving and help them transition from abductive to deductive reasoning.

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Stages, sequence, and scale: Tradeoffs in heuristic mapping designs employed in the instruction of animal lifecycle

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Objective: Visually delineating stages, sequence, and scale to support young children's comparison between and within different species' lifecycles

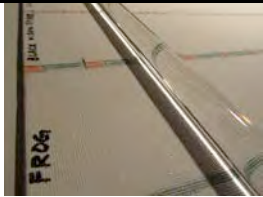



In most elementary school science curricula, students study different animal lifecycles by observing living insects (e.g. monarch butterflies, silkworm moths, milkweed insects) and amphibians (e.g. frogs, salamanders) in their classrooms. In order to support children's comparison between and within different species' lifecycles, four designs attempt to visually break apart developmental stages, sequence of stages, and temporal scale.

Background

The diagrammatic representations and texts used to support instruction in elementary school science curricula do little to support the higher order thinking that children are capable of. In part, this design problem stems from an underestimation of both young children's cognitive capabilities (Brown, Campione, Metz, & Ash, 1997) and the complexity of the scientific content taught in these early classroom encounters. Current instructional materials constrain children's intuitive understandings of proportional scaling of developmental stages and the absolute duration of the species' lifecycles.

Designs: Affordances and Constraints of Four Designs

This initial design work is part of a larger project to support elementary students' understanding of animal lifecycles. These four designs are a first step in articulating insights into the complexity of learning and instruction of this biological phenomena. Many of these insights came from my own interactions with the materials. As Bamberger and Schön (1983) noted, a 'reflective conversation' occurs "between makers and their materials in the course of shaping meaning and coherence" (p. 69). Indeed, it was through the process of designing and building that I came to understand many of the disconnects and opportunities students might encounter with this scientific content.

Lifecycle Timeline	Lifecycle Spinner	Lifecycle Gears	Lifecycle Rolling Stamper
			

Conclusions

Building on these insights, future work will combine auditory feedback and kinesthetic movement in order to foster awareness of time happening (process/ fluid) while physically representing the passage of time (product/ static). It seems that rhythm, both expressed through sound and a child's physical movement, might generate deeper connections about both the proportional scaling of developmental stages and the absolute duration of the species' lifecycle.

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Actions vs. Symbols: Improving a Tangible Programming Interface for Children

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Objective: Understanding Ontological Differences Between Action and Symbol

When children engage in activities that demand analyzing situations, they encounter difficulty in using static semiotic devices, such as symbolic notation, to represent transitory actions, such as an agent's motion; or they confuse the ontological status of their own physical actions as either bearing or not bearing on the situation's focal properties.

Background: Tensions Between Action Knowledge and Symbolic Representations

Sfard (2000) stated that "symbols have the power to turn the extended-in-time, transitory, and invisible into contained-in-space, permanent, and perceptually accessible." Connecting music and math, Bamberger and diSessa (2003) used a digital platform to invoke multiple representations of musical patterns. Their project illustrates the *ontological imperialism* of hegemonic symbol systems, whereby each representation foregrounds particular features, while "ignoring or minimizing others." Prior studies with Project Bloks (Blikstein et al., 2016) revealed children's confusion as they map actions onto symbols. When asked to instruct a stationary avatar to step along an articulated path, they confuse between *one step* and the *two contiguous locations* it traverses. Similar, in measuring spatial distances, young children may count marks (including zero) rather than intervals. My research investigates how ontological differences between action and symbol contribute to students' evident confusion in measuring lengths and in related activities.

Design: Interviews Investigating and Supporting the Action-Symbol Ontological Shift

In the context of mathematics, Radford (2003) discusses *semiotic means of objectification*—objects, tools, linguistic devices, and signs that individuals employ to make apparent their presymbolic intentions and negotiate different properties and meanings of situations.

In the current project, I designed and conducted semi-structured clinical interviews (Ginsburg, 1997) for 1st-grade students centered around three tasks in each of four different maze configurations (see Fig. 1). The first two tasks ask participants to determine the number of squares in the maze and the number of steps it takes to traverse the maze; the last task provides participants with an opportunity to generate their own notation, framed in terms of helping a "robot" token navigate the maze (e.g., Fig. 2). By engaging participants in discussion about their inscriptions, we are able to support them in recognizing the properties and relations that are lost in the translation from action to symbol. We discuss with the students how certain features of the inscriptions, like the *points* of the concatenated loops (rather than the *arcs* of the loops, see Fig. 2), draw our visual attention because they are more figurally salient, punctuated, and countable than other features.



Fig. 1: Kotaro counts the number of steps in a maze; he performs co-speech pointing utterances.

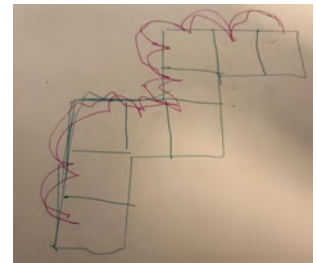


Fig. 2: Tanner's inscription of a maze, with loops (in pink) traversing the squares.

Results and Conclusions From Qualitative Analysis of Two Cases

Cycles of intense micro-genetic analysis led me to focus on three different moments across the data, where participants' dialogue, gestures, and/or inscriptions enabled us to understand their evolving perceptions of action and symbol. Action across space and time is difficult to represent in ways that preserve all relations and properties. However, the transformation of ephemeral actions into visible and/or tangible objects creates opportunities for discussing and reconciling our perceptions of task-focal features. Further research is required to determine how we can work in various contexts to support students in resolving tensions between action, space, time, and their symbols.

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Explicit Oral and Written Reasoning During Science Argumentation

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Objective: Create Material Object to Serve as an Analogy Supporting Scientific Argumentation

The purpose of this design project was to develop and evaluate an assemblable material structure that forms and mobilizes student reasoning during science inquiry by way of constituting an interactive analogy of goal argumentation mechanics.

Background: Reasoning and Science Argumentation

Learning to support a claim with evidence is fundamental to appropriating scientific practice (Erduran & Jiménez-Alexandre, 2008). Science educators and national standards have thus called to enhance the practice of science argumentation throughout K-12 (National Research Council, 1996; National Governor's Association, 2010). Research on argumentation suggests that students are challenged in particular to explain how or why their evidence supports their claim (McNeill et al., 2006), albeit they are quite persuasive and adept at making arguments about personally relevant issues (McNeill & Krajcik, 2011). How might we enable students to use their everyday resources so as to sustain complex reasoning during scientific argumentation?

Design: A Material Anchor for a Conceptual Blend to Support Argumentation

Inspired by the theoretical construct of a *material anchor for a conceptual blend* (Hutchins, 2005), I sought an accessible, common, concrete, cultural analogy for students to encode structural components of their scientific argumentation while they reason about specific content. In a material anchor, "a mental space is blended with a material structure that is sufficiently immutable to hold the conceptual relationships fixed while other operations are performed" (Hutchins, 2005, p. 1562). I created the Build an Argument material anchor (Figure 1), a culturally familiar physical block structure that needs to support a top block, and blended it with an epistemic notion of abstract scientific arguments needing ideas to connect evidence to claims. "Part of the cognitive power of metaphor derives from the fact that it is possible to reason effectively about unfamiliar concepts, which would otherwise be unstable, if they can first be blended with stable familiar concepts" (Hutchins, 2005, p. 1573). Here: base = evidence, supporting columns = connecting ideas or reasoning, and roof = a claim that must be supported. In the blended space, the blocks are experienced as parts of an argument, cuing students to seek ideas (columns) to hold together the overall structure (the argument). In determining the parts of an argument, I borrowed from the seminal work of Toulmin (1958) respecting claims, evidence, and warrants.



Findings: Appropriating the 'Build an Argument' Mechanics to Offer Explicit Reasoning

A pair of 12-year-old female students participated in a pilot trial of the activity. Assigned with scientific inquiry problems, the participants were prompted to sort available evidence according to how it could potentially support claims. Next, they used the Build an Argument kit to explain how the evidence connects to the claim. Finally, they wrote down their reasoning. The session was audio-video taped for subsequent study. I performed microgenetic qualitative analysis of the recording as well as student artifacts in an attempt to reveal implicit reasoning processes. The first finding was that the material anchor was understood and appropriated by the participants to enhance their argumentation. This was reflected in the participants' facile and creative uses of the kit that made evident their utilization of its embedded epistemic criteria. One participant explicitly stating that the kit was helpful. Secondly, the activities with Build an Argument supported student reasoning, as evidenced by their offering more explicit reasoning *during* and *after* this supported activity as compared to *before* it.

Conclusions

Materials anchors for conceptual blends, such as the Build an Argument assembly kit, may be effective means of supporting student scientific reasoning, by way of deploying complex reasoning structures into familiar mechanics of concrete objects.

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Toward Didactical Contracts for Mathematics Learning with Digital Media:

Coordinating Pedagogical Design and Classroom Practices

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Objective: Helping Students and Teachers with Proportional Reasoning using an iPad Application

The objective of this design-based research project is to investigate student-teacher interactions around technology-based activities designed to support the development of proportional reasoning.

Background: a Design-Based Research Study of Emerging Proportional Reasoning

Technology is increasingly ubiquitous in informal settings outside of school, and this ubiquity implicitly shapes students' interaction practices with digital media within formal school settings. At the same time, the accelerated accessibility and affordability of cutting-edge computational devices means that schools are staggering far behind homes with respect to the forms of technology that students engage at each setting. Incorporating technology into the classroom context results in more than simply importing an object: surreptitiously, and willy-nilly, we import students' informal cultural practices and expectations revolving around their previous and prevalent experiences with these familiar technological media.

Design: an Embodied-Learning Technological Device for Developing Proportional Schemas

The Mathematical Imagery Trainer for Proportion (MIT-P) is a device designed for students to discover, rehearse and embody proportional equivalence (Abrahamson & Trninic, 2011). MIT-P 1 was a mechanical pulley system that served us in concretizing our emerging design concept, but did not afford opportunities to learn in accord with our design rationale. We built MIT-P 2, a motion-sensor Wii-mote technological device, in which users remote-controlled virtual objects on a computer screen, with grids and numerals gradually interpolated into the environment as frames of reference in support of student inquiry and, reflexively, in support of re-shaping their embodied know-how in mathematical register (Abrahamson et al., 2011). The MIT-P 3 iPad application (see Figure 1) is intended to support mathematics instructors in facilitating discovery-based learning of proportion.



Figure 1: (a) Screenshot of MIT-P 3 iPad application; (b) 9th grade students working with MIT-P 3 iPad (pilot study).

Findings: Clash of Interaction Practices

A small pilot of 3 volunteering students exhibited how changing the medium (from Wii-mote to iPad) had significant effects on the instructors' ability to facilitate their intended interview protocol. Specifically, students in the pilot study were accessing features of the mathematical artifacts out of protocol. Therefore, for subsequent whole-classroom implementations at a public high school, we redesigned the activity sequence in line with students' interaction norms: We told students to use all features as tools for accomplishing a manipulation task. As Brousseau (1997) argues, we must create for students opportunities to take ownership of a situation or activity and become responsible for their learning (the process of *devolution*). Microgenetic analysis of the classroom implementation (Schoenfeld, Smith, & Arcavi, 1991) illuminates how students indeed took ownership of the situation. For example, two independent groups requested a ruler to measure the vertical length of the bars. Shortly after, these students realized that an embedded gridline would enable them to measure the bars. This example shows how students took initiatives toward mathematizing features of the display in support of accomplishing activity goals. In so doing, the students discovered latent proportional relationship, in line with the educators' instructional objectives. Overall, student groups in the classroom implementation exhibited several strategies for making the bars green and utilized mathematical discourse relating to proportionality in MIT-P 3.

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Discovering Correlation With Avalanche™ 2.0

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Objective: Enable Students to Differentiate Correlation and Causality

When two events co-occur, they may be causally related, correlated, or independent, and yet humans are inclined to perceive them as causally related (Piaget, 1960). Differentiating between correlation and causation is essential for statistical literacy. This project sought to engineer activities that create opportunities to develop this differentiation.

Background: Text-Based Realistic Situations vs. Artifact-Based Interactive Materials

Students typically encounter the concept of correlation in high school through reading, discussing, and reflecting on verbal descriptions of realistic situations (Common Core). It could be that students' persistent difficulty with the concept results from a lack of opportunities to experience the situations firsthand in their spatial-temporal dynamical complexity. Providing firsthand experiences would better align pedagogical activity with cognitive theory (Lave, 1991) and professional practice (Schön, 1983). In particular, sensorimotor interactions with artifacts that extend the mind can foster neural foundations for simulating these interactions offline (Wilson, 2002). In turn, recurring experiences of consistent sensorimotor patterns give rise to conceptual structures (Varela, Thompson, & Rosch, 1991). Students may thus better understand correlation through engaging with novel interactive artifacts latently bearing the targeted conceptual systems rather than with text-based quasi-realistic problems.

Design: From Action to Representation in Differentiating Causation and Correlation

Avalanche 2.0 is a design-based research project, in which artifacts, methods, and theory co-evolve iteratively. The design repurposes Parker Brother's 1965 game, *Avalanche*™ to help students develop situated, pre-symbolic, sensorimotor notions of causality vs. correlation. As in the classic activity, students adjust rotating pegs and drop marbles from holes at the top of an inclined board. Yet for *Avalanche 2.0*, the interviewer places two marbles on the board and prompts the student to drop a third marble from the top such that all three marbles reach the bottom. Marbles are placed at positions in which either: (1) Marble A is dropped from the top and hits Marble B that, in turn, causes Marble C to fall; or (2) Marble A causes both Marble B and C to fall. In the culminating iteration, students read a set of realistic narratives that are structurally analogous to the various *Avalanche 2.0* situations (e.g., waves wash crabs onto the beach, the crabs topple a sandcastle). Students model the story either by drawing a static diagram on paper or by creating a structurally analogous marble set-up on the board and "running" it.

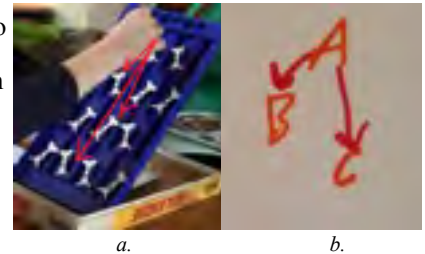


Figure 1. (a) A child enacts correlation. (b) Her diagram of a correlation story.

Methods

Six participants of various ages (8-17) were interviewed. The task procedure evolved as follows over four iterated study cycles. Beginning from the initial pilot study and through to the culminating procedure, students:

- 1) completed the simple *Avalanche 2.0* protocol with the interviewer;
- 2) worked through the protocol, then read a set of stories that modeled situations of either causation or correlation and drew diagrams of these events;
- 3) read story problems and were asked to draw a diagram of the events in each story; then they worked through the *Avalanche 2.0* protocol with the interviewer; and
- 4) worked through the *Avalanche 2.0* protocol with the interviewer, read causation or correlation stories, and were prompted to model the events first by drawing diagrams and then by enacting the events on the *Avalanche* board.

Task-based clinical interviews were videotaped and multimodal utterances were interpreted and transcribed, with particular attention to emerging articulations of correlation vis-à-vis the available media and forms. Specifically, I sought to detect relations between students' most frequent communication modality and overall success in articulating correlation. I investigated whether the structural analogies between narrative, diagram, and simulation would occur to the students spontaneously or by prompts, and whether noticing these analogies contributed to more formal articulations of correlation.

Results, Discussion, and Conclusions

Working in the physical problem space, most students developed proficiency with a set of distinct diagrammatic models for different types of co-occurring events. In particular, they were able to draw diagrams correctly to represent the events of each *Avalanche 2.0* situation, and they used various techniques to articulate their emerging understanding of correlation. Students gestured prior to verbally expressing their understanding of correlation, which, as Lave (1991, p. 345) wrote, may "serve to package theoretical conceptions into semiotic entities that can be used symbolically in a community of practice." Yet students whose gestures about the *Avalanche 2.0* events did not evolve into verbal articulation of these events were later less proficient in modeling the stories, both via *Avalanche* enactment and in generating symbolic models of the events.

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An Embodied Approach to Derivatives

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Objective: Increasing Access to Calculus

Calculus is traditionally a gatekeeper to higher education, particularly in STEM fields. An accessible approach to calculus could make the course and the educational and career opportunities it carries available to a broader range of students.

Background: An Embodied Approach to a Traditionally Symbolic and Graphical Problem

Students tend to conceptualize functions as strings of symbols (Thompson, 1994), overlooking the functional characteristics that those symbols represent. In particular, students may recite the formula for the limit definition of derivative (Figure 1)

$$f'(x_0) = \lim_{h \rightarrow 0} \frac{f(x_0 + h) - f(x_0)}{h}$$

Figure 1. The limit definition of derivative.

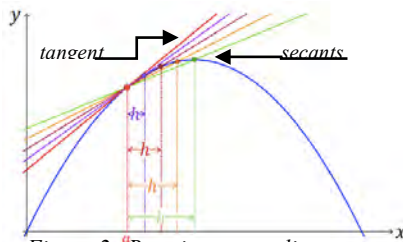


Figure 2. Rotating secant lines approximate the tangent.

while simultaneously failing to recognize that a rotating secant line approximates a tangent line (Figure 2), where this relationship forms the graphical basis for the former definition (Orton, 1983).

Embodied design aims to create physically situated challenges such that the action-perception behaviors toward solving these challenges become cognitive resources (Abrahamson, 2014). Faced with a physical problem, students first experience secants and tangents at a hands/body-on level where their movements can be motivated and constrained by a field of promoted action, a physical setting that guides students toward specific movements (Abrahamson & Trninic, 2015). Once moving in mathematical ways, students encounter domain-specific tools and symbols with which to formalize their physical strategies, translating their movements into mathematical terms. Resulting formal expressions carry the target concept as well as students' personal, physical experiences (Abrahamson, 2014).

Design: The CalcMachine – an Artifact for Embodying Derivatives

I sought to develop a physical environment in which students' intuitive bodily actions contribute to their making sense of the limit definition of derivative. The physical model contains a metal curve approximating a parabola and a drawing bar that travels along the curve, attached by two points (Figure 3). Students trace against the bar to draw, moving in ways that are perceptually and physically guided and constrained by the environment. Suggested configurations of lines (Figure 3) are designed to promote movement relevant to reasoning about secant and tangent lines. Prompting students to reflect on the strengths and limitations of their movement schemes, the activity aims to orient students to the relationships between the curve, their movements, and the configurations they can produce.

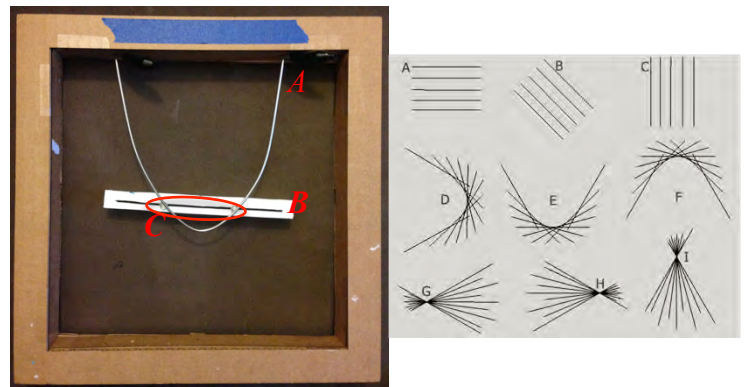


Figure 3. (left) The physical model includes (A) a parabolic curve, (B) a drawing bar, and (C) connection points. (right) Suggested configurations.

This environment is intended as a field of promoted action relevant to reasoning about secant and tangent lines, the basis of the limit definition of derivatives. Mathematical tools such as grid paper or labels for the points could prompt students to express and generalize their physical experiences using normative mathematical forms.

Findings

Participants in a pilot study spent significant time orienting to the model's operation and use as a drawing tool. This work offered insight into participants' learning about the model but did not indicate significant mathematics learning. Future work will focus on connecting bodily actions to the mathematics. Centering such physical action as an academic resource holds promise for meaningful learning that is rooted in students' own experiences.

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It Takes Two to Vector: A Collaborative Embodied Design for Physics

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Objective: Design Learning Activities That Make Physics Concepts Accessible to All Students

Physics concepts are notoriously challenging for K-12 students. For students to build physics concepts on their everyday know-how, often they must reconcile their implicit sensorimotor being in the world with disciplinary forms and procedures pertaining to these same accomplishments. Educational designers seek to enable this reconciliation.

Background: An Embodied-Design Approach to Students' Physics Learning Difficulties

Physics concepts, such as vector summation, can be difficult to learn when they demand an alternative construction of familiar situations. Yet reform-oriented educational researchers stipulate that all instruction should begin with what students know (Smith, diSessa, & Roschelle, 1993). Thus, for students to endorse alternative constructions of reality, educational designers must develop instructional methods to support meaningful assimilation of conflicting views.

The *embodied design* framework informs the selection or generation of artifacts that solicit students' effective naïve ways of perceiving and moving even as they enable guided semiotic shift into complementary disciplinary constructions of the same situation (Abrahamson & Lindgren, 2014). When instructors subsequently introduce into the task space symbolic artifacts, such as a grid, students should recognize therein potential utilities, for example as frames of reference, to better enact, evaluate, or explain their naïve views. In so doing, students signify their know-how in disciplinary forms, thus bridging the epistemic gap between tacit and cultural views on situated concepts.

Design: From Collaborative Manipulation to Physics Concept via Utilizing a Symbolic Artifact

Symbolic artifacts (Sfard, 2002) are the variety of inscribed forms (e.g., a grid or alphanumeric notations) that may support *epistemic actions* (i.e., information seeking; Kirsh & Maglio, 1994). Students collaborating on a task-based pedagogical activity may use symbolic artifacts to render epistemic actions mutually intelligible, thus generating consensual meanings and shared inferences.

A pedagogical activity was designed for two participants to collaboratively solve the problem of coordinating the joint goal-oriented manipulation of a material object, specifically the co-navigation of a wooden figure toward a designated location (see Fig. 1, left). Students are then offered symbolic artifacts (the chessboard grid) as potential resources for enhancing their performance. They are instructed to determine the best performance strategy. Students then create an inscription (see Fig. 1, right) to represent their optimal strategy. Students first do the task upon the blank side of the chessboard and inscribe their solution. Next, they do the task on the gridded side of the chessboard and again inscribe their solution. The grid should serve as a means of precipitating a shift in students' perception of the space and actions therein from continuous to Cartesian.

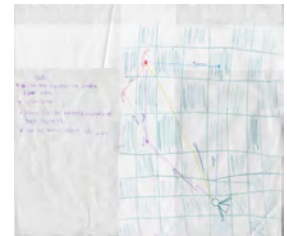


Figure 1: (from left) A two-armed wood figure stands on a gridded space; students co-manipulate it toward a target location. An elaborate inscription, with paths, generated by a pair of 14-year olds in planning their joint actions.

Methods: Piloting the Pedagogical Intervention

A pair of 14-years old children participated voluntarily in protocol-based tutored trials of the activity. Micro-genetic qualitative analysis of the video recording was conducted to formulate a coherent account of their solution processes.

Conclusions: Symbolic Artifacts Stimulate Semiotic Shift in the Meaning of Perceptual Displays

In the course of appropriating symbolic artifacts as new frames of reference for enhancing their joint problem solving, students begin to perceive the objects and actions in a new way. This semiotic shift may prepare the students to reconcile their naïve conceptions of a perceptual display with its normative disciplinary formulations. Future work will expand this embodied design by scrutinizing the evolving meanings of the path/force arrows students inscribed.

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Learning Mathematics by Reconciling Complementary Perceptual Constructions of a Common Display: The Case of an Innovative Design for Complex Numbers

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Objective: Supporting a Cognitive Shift between Cartesian and Polar Representations

Secondary math students should be able to shift between alternative formal representations of curricular concepts (Nation. Gov., 2010). In the case of complex numbers, these alternative representations are Cartesian and polar. Yet shifting between these representations poses challenges in high school and later in college (e.g., Ciptowiyono, 2015).

Background: Mathematical Objects Are Constituted Through Their Representations

My project adopts the semiotic perspective on mathematics learning (Bartolini Bussi & Mariotti, 2008). Individual students constitute mathematical objects through semiotic activity, for example by generating and interpreting diagrams and symbolic notations or making sense of an instructor or peer's multimodal utterance. From this view, students' challenge of shifting between different representations of a concept becomes the challenge of recognizing the same mathematical object through these different representations.

Design: The SeeComplex Tool and Find the Triangle Activity

In approaching the design of educational solutions to this instructional problem, I used principles of embodied design (Abrahamson, 2014) to analyze, phenomenalyze, and implement the semiotic shift as a bidirectional transition between two complementary perceptual constructions of one and the same display, a right triangle. If a right triangle on the plane is perceptually defined as having its base on the x-axis and its hypotenuse starting at the origin, it can be constructed in terms of either

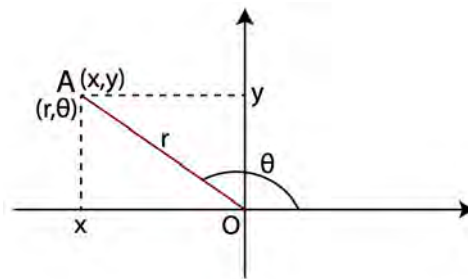


Figure 1. The AOX triangle bridging Cartesian and polar meanings of complex numbers.

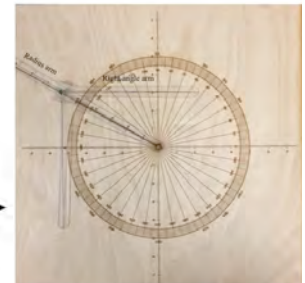


Figure 2. The SeeComplex tool.

Cartesian coordinates (base and height) or polar coordinates (hypotenuse and the angle between the right side of the x-axis and the hypotenuse, i.e., theta; see Fig. 1). I hypothesized that the right triangle, by virtue of bearing structural properties of each of the two representations, could act as a conceptual common ground for bridging the two representations. As such, the desired semiotic shift between Cartesian and polar representations of points on the plane could be reduced to coordinating Cartesian and polar visualizations of the right triangle. This hypothesis was operationalized in the material form of *SeeComplex*, an instructional artifact of my design (see Fig. 2). This artifact served in facilitating the *Find the Triangle* activity that solicited the two complementary visualizations of the triangle.

Methods and Results

Four pairs of UC Berkeley freshmen students participated voluntarily in 45-minute videotaped interviews, facilitated by the author, in which they used the *SeeComplex* device to work on the *Find the Triangle* task. The videos were transcribed, and these documents as well as students' scratch work were micro-analyzed qualitatively. Results of this analysis demonstrate that the student pairs took advantage of the provided opportunities by expanding their knowledge of the right triangle to productively relate the two representations of complex numbers.

Conclusions

Corroborating embodied-design research, the project demonstrates in a new mathematics domain that a visual display comprising perceptual properties of two representations of the same concept can be employed in mathematics-education design to support student conversions between the corresponding semiotic content.

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'Harvesting' Ecosystem Dynamics Through a Computational Model of a Garden

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Objective: Link Experiential Learning to Classroom Content via Accessible Technological Tool

Rationales for hands-on learning experiences, particularly in extra-curricular environments, abound. Given suitable tools and technology, discoveries made in real-life settings can be built upon and re-visited in the classroom. In particular, this project aims to connect student observations of garden ecosystems to the scientific practices of developing and testing models.

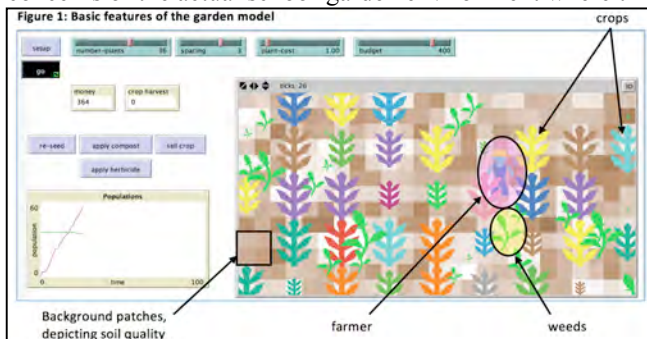
Background: Challenges of Outdoor Education and the Affordances of Agent-based Models

Whereas school gardens have been adopted by many as offering valuable outdoor learning experiences, classroom curriculum is not geared to incorporate the rich academic opportunities that these experiences could potentially offer (Williams & Dixon, 2013). Despite the gardens' numerous psycho-social and nutritional benefits (Ozer, 2007), construction and maintenance of gardens requires dedicated attention, funds, and curriculum, so that teachers and principals hesitate to invest in gardening programs (Graham et al., 2005). With the unveiling of Next Generation Science Standards, teachers are tasked with creating new models of instruction and assessment, yet few structures exist connecting these standards to the outdoor environment.

This project attempts to solve issues both of gardening-based academics and science standards by supplementing these with a third curricular element, computational literacy practices. In particular, agent-based modeling enables students to investigate and reason about complex scientific phenomena, such as garden ecosystems. Used to enrich instruction in many scientific domains, modeling-and-simulation environments such as *NetLogo* (Wilensky, 1999) allow users to manipulate a system's behavioral rules so as to understand how macro-scale phenomena emerge from micro-scale interactions. As a classroom resource, NetLogo models minimize time and space constraints, increase epistemological pluralism, allow for variety in data-driven inferences, and encourage mathematical and computational thinking; these practices are highly aligned with K-12 NGSS (NGSS Lead States, 2013). The models are accessible to a wide range of ages and skill levels and have been shown to deepen and enrich student comprehension of the content they dynamically animate (Wilensky & Reisman, 2006).

Design: Instructional Sequence Incorporating a NetLogo Model of a Garden Ecosystem

For this project, I designed and constructed a model of a garden ecosystem as well as a variety of tasks (see Figure 1, below). Through iterated cycles of prototyping, strategic planning meetings, and debugging sessions, the virtual garden came to life and ultimately became a space to examine soil quality, budgeting, weed growth, and the effects of plant spacing, all real concerns of the actual school-garden environment where this tool is soon to be piloted. Toward designing a middle-school



gardening unit, I conducted 4 pilot interviews with Grades 6 and 8 students. They were each shown the model, asked to run it a few times under different parameters, and make predictions about the utility of particular functions. They also explored many features and offered their own perceived connections to math and science content. Data analysis revealed students' various strategies for orienting into this virtual environment, as well as the intelligibility of interface features. Ultimately, the model should represent the actual school garden and enable students to simulate its authentic problems through modeling-based inquiry. Ongoing analyses,

interface design, and debugging will allow for the continued development of a series of tasks by which students can progress in their knowledge of gardens, science, and computer-based modeling.

Conclusions

Technological tools are important resources for students to avail of learning opportunities inherent to experiential education, while satisfying current academic standards. In designing these resources and their corresponding instructional sequences, the interests and abilities of students and teachers must be simultaneously taken into consideration to promote optimal results.

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Exploring for Cognitive Affordances in Audio Renderings of Cartesian Data

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Objective: Identify Affordances and Constraints of Presenting Graphical Cartesian Data in the Audio Modality Rather Than the Visual Modality

Cartesian representations of large data sets demand a perceptual search for global patterns configured by particulate data. This search can be encumbered in the case of “noisy” data sets. Visual representations of noisy Cartesian data in particular are difficult to interpret and susceptible to misleading perceptual heuristics and biases. Sonification—acoustic rendering of information from other modalities—may offer a solution. Yet what are the affordances and constraints of audio-graphical sense-making? Can we hear complex data better than see it?

Background: Visual Graph Cognition and Aural Cognition

When we look at a graph, we construct the sensory information via a process mediated either by the innate grouping principles detailed by the Gestalt laws of perceptual organization (Wertheimer, 1938) or by the emergence of structure through the invocation of schema (Pinker, 1990). Ullman (1984) calls this processing of visual information a *visual routine*. Theories of aural cognition, however, have been less thoroughly characterized. Perception theorists argue that Gestalt-like principles guide our interpretation of auditory sensations (Bregman, 1990). Other theorists from music cognition argue that sense-making of sound is an active organization process bound to the search for sound figures, that is auditory phrases, yet also shaped by the ontology implicit to musical notation (Bamberger, 2006).

Design and Methods: A Visual → Audio graph

A visual representation of the function $f=x$ was created with discretized data and additional noise added to the function. We then created an audio representation of the same data by converting each data point to a pitch based on its position on the y -axis. Using these stimuli, we engaged a Humanities Ph.D. student in a task-based, semi-structured interview consisting of activities that involved describing, extrapolating, and interpreting both visual and auditory graphical items. The interview lasted about thirty minutes and was audio-video taped for subsequent qualitative micro-analysis. The analysis centered on the student’s multimodal utterances, in particular her use of gesture and imagistic / metaphoric language.

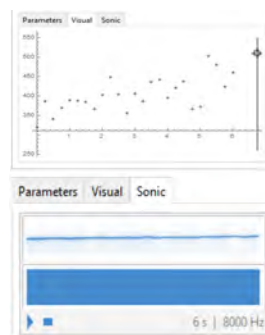


Figure 1:
Top—A visual representation of the function $f=x$, with added noise;

Bottom—An audio representation of the same function.

Results and Conclusions

Results suggest that the graph modality affected the participant’s *mid-level construction strategy* (Levy & Wilensky, 2008), a heuristic mechanism for negotiating particulate data in search of global patterns. The visual graph triggered macro-to-mesa sense-making, whereas the audio graphs triggered micro-to-mesa search for global patterns. This mid-level construction strategy mirrors theories of musical cognition that describe the active formation of sound figures in musical perception (Bamberger, 2006). Interpretation of the visual graph was additionally guided by the participant’s top-down expectation frames for a graph’s features and function. Finally, the audio data carried more affective associations than the visual. Whereas these associations made for greater engagement, in turn they exacerbated the tension between the *properties* of each individual data point and its *function* within the pattern as a whole. We thus conclude that non-visual data representations may hold some conceptual advantages with respect to the learning of certain content, especially in contexts where it would be of benefit for agent-based sense making to be employed.

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Building Bridges: Uniting students, researchers, and teachers to improve a course

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Objective: Build a More Meaningful Pre-Service Teacher Classroom Placement Experience

This project builds bridges between three groups of stakeholders involved in preparing high school Mathematics teachers: pre-service teachers (PST); practicing teachers who mentor them; and teacher educators/researchers. The study is grounded in the Cal Teach teacher-ed. course at UC Berkeley. The research will evaluate an innovative intervention, in which PST and their mentor teachers collaborate on an inquiry project focused on some problem of classroom practice of their own choice.

Background

“Pitfalls” in Learning to Teach From Experience. Researchers recognize that PST struggle with the conflict between their experiences in classroom placements and in coursework (Ronfeldt & Grossman, 2008). The challenges PST face negotiating that conflict can inhibit their learning and lead them to selectively interpret theories and practices to fit the realities they experience (Feiman-Nemser & Buchmann, 1983; McDonald, Kazemi, & Kavanagh, 2013).

Conflict Can Be Productive. Ward, Nolan, and Horn’s (2011) research shows that if appropriate supports exist, the conflicts that student teachers experience can be productive. They identify the notion of “productive friction” and describe how PST identity develops in between figured worlds (Horn, Nolen, Ward, & Campbell, 2008). I extend their idea of “productive friction” from student teachers to all PST, and hypothesize that some conflict can be leveraged to support PST learning by reimagining the interaction between novice and expert during the placement experience

Design: The Collaborative Inquiry Project

Rather than leave the work of negotiation between research and practice to the PST alone, this project situates it in an inquiry project conducted collaboratively by PST, practicing teachers, and researchers. The three stakeholders bring different types of resources, and the study aims to investigate negotiations among them as they all work to value, understand, and integrate their resources productively. Initial work involves five local high school math teachers, nine Cal Teach students enrolled in EDUC 130, and two course instructors. To date:

- High school teachers and course instructors met to choose two aspirational goals for their teaching and several projects that support those goals and are manageable for PST.
- The Cal Teach students met with their mentor teachers to select a project. They also developed initial questions to guide observations in classrooms and reading in EDUC 130 that accompany the project. This was supported by an adaptation of the TRU Math Conversation Guide (Baldinger & Louie, 2015).

Initial findings show that the high school teachers see a need for reimagining the role of Cal Teach students in their classrooms. One teacher described feeling that Cal Teach students “parachute” into her classroom when they teach a lesson, a metaphor that captures a common impression that Cal Teach students do not get to know the classrooms they visit and sometimes interact with students in ways that run against the teachers’ norms and goals. All five expressed desires for more time to talk with their Cal Teach students to explain their teaching practices and provide guidance for what to do and look for in the classroom. Furthermore, it appears that mentor teachers and PST could engage in productive discussions about classrooms grounded in evidence while focused on a shared project and supported by an observation framework like TRU.

Conclusions

It is still too early to draw conclusions, however work done to date suggests promise in helping PST focus their interactions and observations in classrooms and use materials from coursework in planning and reflecting on a lesson. The project has also acquainted the high school teachers with the goals and content of the EDUC 130 course instructors and vice versa. The development of these two “bridges” so early in the project demonstrates potential for future work.

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A Number-Line Estimation Game: Highlighting Proportional Schemes

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Objective: Enabling Children to Incorporate the Splitting Strategy Into the Number Line

Students need to adopt normative cultural practices for the number line (NL): (a) viewing it via a proportional lens; and (b) using splitting strategies in estimation tasks. This initiation can be most robust, if it is mediated through embodied experience.

Background: The Significance of Number Line Estimation Tasks and the Splitting Strategy

Being a cultural artifact, the NL representation is governed by several conventions. Notably, integers are placed on the NL in a way that respects *order* and *equidistance*. Extensive empirical work, in which *number line estimation* (NLE)¹ tasks were administered to children of various ages, has shown that students throughout elementary school exhibit difficulties in appropriating the *equidistance* convention (Saxe et al., 2013; Siegler & Opfer, 2003). And yet success in bounded NLE tasks is correlated, and even causally related, to general numerical abilities of elementary school students (Booth & Siegler, 2008).

Some researchers interpret these data as indicating a structural-developmental shift in the spatial representation of numbers (i.e. the *mental number line*) (Siegler & Opfer, 2003). Yet recent findings from eye-tracking (Schneider et al., 2008) and error-pattern (Link et al., 2014) analyses point to *splitting*² being the key strategy employed in correct solutions to NLE tasks. This leads to a reinterpretation of previous results linking success in NLE tasks to general numerical ability; perhaps the most important aspect of the NL, the one correlated with numerical achievement, is the practice of applying proportional heuristics when solving NLE tasks rather than constructing the representation itself, as has been the focus so far.

Design: A Number-Line Estimation Game

The design proposed here is a NL game that incorporates NLE tasks within a physically constructed NL. The NL is realized as a line drawn on an 11-inch long corkboard. Numbers are positioned on this NL by placing numbered pins on the board (see figure). This 3D setting allows participants to interact with the NL in novel ways. Unlike static tick marks, pins can be moved around, the experience thus encouraging an internalization of flexible number distribution. Moreover, the material differentiation of pins and the NL may enhance cognitive differentiation between numerical symbols and the linear frame of reference. Paper strips replace Cuisenaire rods, the traditional supporting materials that are rigid and thus do not easily lend themselves to embodying *splitting*. Importantly, the activity facilitator prompts students to engage proportional schemes and splitting strategies.



Two 5th grade students solve NLE tasks. To enact the splitting strategy, Bob folds paper strips (left), and Clara uses her hand to visually estimate the midpoint (right).

In order to empirically test the design, semi-structured (pilot) interviews with three Grade 5 students were conducted. A variety of NLE tasks were administered, each followed by questioning designed to gauge students' reasoning. The ordering of tasks was deliberately varied between interviews so as to evaluate the effect of this dimension.

Results and Conclusions

The NLE game design proved to be extremely successful in eliciting students' reasoning about the NL in general, and its proportional properties in particular. For 2 out of the 3 children interviewed, folding a paper strip supported the incorporation of splitting into reasoning about the NL. Specific assessment features, e.g., the selection of numerical items, may dramatically affect children's selection of NLE solution strategies: 2 children exposed to the same sequencing of tasks generated almost identical solution methods, whereas a third child, who experienced a different task sequence, exhibited different behavior.

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¹ In NLE tasks participants are given a number line with two labeled numbers and are asked to estimate the position of a third.

² Splitting (or halving) entails locating the midpoint between two numbers placed on a NL toward locating a third number.

Trees: Fostering the discovery of logarithms

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Objective: Design an Activity Enabling Deep Understanding of Logarithm and Exponent

Algebra students are expected to understand the mathematical operations of logarithm and exponent. Yet many students fail to understand these operations and their reversibility. These challenges can be ascribed to the different notational formats of these reversible operations as well as to student difficulty in grounding these operations in familiar contexts. Educational researchers believe that students can achieve deep understanding through guided conceptual discovery (Abrahamson, 2012; diSessa, 1991). In particular, Martin and Schwartz (2005) demonstrate pedagogical advantages of having students struggle to represent a familiar math concept using unfamiliar concrete resources. This study aimed to design and evaluate an activity, including artifacts and task, for students to discover the mechanism and expression of logarithm as reversible to the exponent.

Background: In Search of an Accessible Model of Logarithm-Exponent Reversibility

Educational researchers of mathematical cognition and instruction have sought effective pedagogical designs for students to learn the meaning of logarithms and exponents. For example, Wood (2005) argues that students should learn how logarithms are applied; Panagiotou (2011) suggests an historical approach. Yet neither of these designs would create opportunities for students to discover and own the operations. What naïve personal knowledge could potentially serve students in discovering these concepts? Confrey and Smith (1995) argue for a restructuring of multiplicative concepts, such as exponents and logarithms, drawing on the notion of splitting rather than repeated adding. The tree model could provide a splitting-based representation of the operational reversibility of logarithm and exponent. The tree model was selected for this study.

Design, Implementation, Evaluation, and Results

We selected concrete “node” and “edge” construction materials as resources for building exponential trees. We engaged two pairs of 12-year-old students in task-based semi-structural interviews consisting of 3 collaborative activities: (1) generalizing the properties of exponential trees; (2) pair construction game to surface more language; and (3) constructing trees with different pieces of information (number of leaves [exponent], height of the tree [power], and type of tree [base]). Each interview lasted approximately 80 minutes and was audio–video taped for subsequent qualitative micro-analysis.



Figure 1. Left: Model of a “2-tree” with 3 levels; Right: A participants’ representation of a tree with 81 leaves.

The tree model rendered the reversibility of logarithm of exponent transparent for the participants. The activity furthermore enabled multiple conceptual entries. In building the trees and solving emergent problems, the participants spontaneously created multiplication–division progressions. The study also revealed interesting aspects of students’ meta-cognitive orientations toward construction-based mathematics activities. Whereas educators implicitly differentiate between mathematical concepts and their diagrammatic instantiations, students initially regard these as ontologically undifferentiated.

Conclusions

We see pedagogical potential in instructional activities that instantiate the splitting-based conceptual model of logarithms and exponents. The activities may enable students to re-invent the definition of a logarithm and discover its reversible relation to the exponent: Students who have studied exponents but not logarithms come to articulate logarithms as the logical inversion of exponents by seeing that these operations are two complementary visual–operational interpretations of one and the same diagrammatic structure. We recommend further research into including in algebra lessons activities based on these materials.

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Dynamic Embodied Angles in a Simulated Restorative Planetarium

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Objective: Embodied Restructuration of Euclidean Angles

In traditional geometry education, the dominant medium is paper (Papert, 2004). Thus, geometrical objects, e.g., triangles, are inscribed as static forms lying on a plane perpendicular to our line of vision. Whereas static forms are conducive to measurement and analysis, they implicitly entrain a static ontology of geometrical elements, such as angles (Thompson, 2013). A dynamic perspective on angles, grounded in embodied movement, introduces alternative geometrical ontologies, where angles are trans/formed by the body (Smith et al., 2014). This dynamic view presents angle measures as ratios out of the entire circle.

Background: A Realistic Embodied Perspective on Angles, Incorporating Self and Environment

Freudenthal's (1971) pedagogical philosophy, Realistic Mathematics Education (RME), promotes an ecological approach to quantitative reasoning designed to narrow the prevailing epistemic gap between embodied know-how and formal subject matter (Gravemeijer, 1994). Situating mathematics education may, thus, reconcile naturalistic experience of angles as *dynamical-egocentric* and normative disciplinary representations of angles as *static-allocentric*. Such restructuring of angles could broaden access to the discipline by diversifying its prerequisite epistemic practices (Turtle & Papert, 1991; Wilensky & Papert, 2010). The pedagogical framework *embodied design* guides such mathematical restructuring by theorizing learning as dialogic negotiation between naturalistic perceptuomotor activity and cultural-historical forms (Abrahamson, 2019).

Design: Geometry Planetarium – Enacting Angles in a Navajo Archeo-Astronomy Environment

Geometry Planetarium (GP) is a designed learning environment simulating essential perspectival qualities of Navajo archeo-astronomical practice in dialogic negotiation with Euclidean geometry. GP utilizes cultural-historical forms of *astrometrical* perception, which posits spatial intervals between heavenly bodies as subtending two egocentric visual marks, whereby distance is gauged as an expanding egocentric angle. GP (Fig. 1) is an enchanted enclosure with other-worldly ambience. This environment creates opportunities for young students to reinstate Indigenous sensorimotor phenomenology of angle as egocentric dynamical enactment, replacing formal symbolic computation with realistic sensorimotor experience. In GP, the child becomes the vertex of a projected triangle, whose base is the gauged celestial interval. Young Chaunese compared the magnitudes of two objects in the GP sky (Fig. 2). She then explained her comparison by rotating her stretched arms outwards to embrace each imagined expanse. Finally, she was guided to repeat the double-pointing gauge by using an innovative device composed of two rotating dowels fastened at the base (Fig. 3). A protractor attached to the base enabled her to cite the angle measure of the expanse.



Fig. 1: Outside view of the Geometry Planetarium

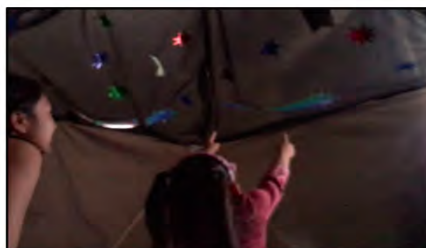


Fig. 2: Chaunese gauges the length of a shooting star by subtending its stretch.



Fig. 3: Dual pointer with affixed protractor.

Conclusions

Acknowledging and using the egocentric dynamical perspective on astronomical magnitude as embodied angle revitalizes Indigenous knowledge and integrates it with mathematical disciplinary knowledge to advance meaning in geometry education.

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Mending Perspectives on Digital Maps: Reconfiguring a Non-Visual World

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Objective: Design a Training Protocol for Learning How to Use Digital Maps

Whereas normally sighted people rely on vision as a critical sensory modality for spatial navigation, people with visual impairments (VI) use auditory and tactile modalities (Cappagli & Gori, 2019). Newly developed digital maps utilize the auditory sense to preview space before travel, yet to capitalize on these resources, the VI field must develop training protocols.

Background: Blind and Visually Impaired Travelers' Unique Sensory Needs

Throughout their K–12 schooling, students who are blind and visually impaired (BVI) have a secondary curriculum, the Expanded Core Curriculum (ECC), designed to support their unique learning needs (Hatlen, 1996). The ECC comprises nine areas, including *orientation and mobility*—safe, effective, and efficient travel skills; and *assistive technology*—the use of specialized technology to access information. A recent technological innovation, SAS Graphics Accelerator (SGA), combines these two ECC areas in a single platform for exploring digital maps before traveling the terrain. SGA is a Google Chrome Plug-In designed to convert maps created using Google's MyMaps into accessible digital maps (Figure 1) that can be explored using non-visual methods. This project aimed to create a heuristic training protocol on the use of SGA digital maps to allow for independent exploration and travel of new spaces.



Figure 1. SAS Graphics Accelerator version of Adventureland with 11 points of interest.

Design: An Instructional Protocol for Orienting to Digital Maps Prior to Travel

For this project, I used MyMaps to plot and label points of interest in Disneyland Park, California. I then created several maps, exported them into SGA, and sonified points of interest. Consistent with design-based and participatory-design methods (e.g., Cobb et al., 2003; Hourcade, 2017), I involved key stakeholders in my iterative process of creating an instructional protocol for the use of digital maps. For the first iteration, I worked with a blind stakeholder on using SGA to explore a digital map of a familiar area. I then created a single map of Disneyland Park with over 150 points of interest: lands, rides/attractions, restroom, restaurants/food carts, shopping locations, and key path intersections. Recognizing that the cognitive load was too great and required too many mental stimuli (Kirsh, 2010) for the training protocol to be effective, I engaged in an email exchange with one stakeholder and two more Zoom sessions with a blind stakeholder. These sessions resulted in creating a new set of maps, including an overview of the Disneyland Lands to use as an introduction to the SGA program, a map of each land with points of interest, and maps of paths through the park. The sessions were recorded for subsequent micro-genetic qualitative analysis.

Study: Detecting and Negotiating Diverging Perspectives

Analysis revealed a communication breakdown between two people orienting perceptually toward the same domain of scrutiny (Goodwin, 1994) via different sensory modalities (visual, auditory). Interpreted as different Subject–Instrument–Object configurations (Vérillon & Rabardel, 1995), these competing orientations apparently centered on egocentric (street-view projection) versus allocentric (bird's-eye view) interpretations of map features with respect to each other's utterances. Yet this breakdown was a pedagogical necessity. Once revealed, a subsequent mending of *shared orientations* to *shared referents* led to the participant re-instrumentalizing the map as a resource for combining the two respective perspectives into a productive representation of the physical space to be traveled.

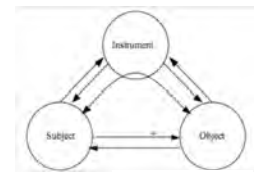


Figure 2. Instrumented Activity Situations

Conclusions

When a teacher and a student share a sensory display, they often orient differently toward it, because the student has not yet developed new perceptual habits. The teacher can clue into these perceptual differences by closely listening for communication breakdowns, when the student's references to the display appear incompatible with their own. Designers cannot anticipate all breakdowns. Involving key stakeholders as representatives of the population of interest throughout the iterative design process, for example, in creating a training protocol on the use of SGA digital maps, allows for the emergence of productive instruments.

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The Function of 2D Representations in the Construction of 3D Objects

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Objective: Understand How Students Make Sense of Orthographic Projection Drawings

Students face difficulties when tasked to create 3d solids from 2d orthographic projections. Using a task-based clinical-interview instrument, this design-based research project explored students' challenges and opportunities with 2d–3d content.

Background: Orthographic Drawings as Semiotic Structures

Drawing is creating 2d representations of 3d objects, and yet even young children perform this task with some minimal proficiency (Sinclair et al., 2016). Refining this skill to a professional level, however, requires organized instruction, and yet such instruction is rarely offered in mainstream schooling (Ben-Chaim, Lappan, & Houang, 1989).

Translating between 2d and 3d forms requires applying specialized techniques that may violate tacit routines of naturalistic perception, such as through explicit attention to perspective (Sinclair et al., 2016). Per semiotics theory, 2d representations—such as orthographic projections—bear dense figural directives for generating 3d analogs (Widder, Berman, & Koichu, 2019). Mastery of this conceptual domain is the capacity to convert each form into the other, $2d \leftrightarrow 3d$ (Okumus & Hollebrands, 2019).

Current methods of teaching $2d \leftrightarrow 3d$ lack dimensionality and modularity: (a) worksheet-based exercises simulate depth only via manipulations to the length and width of the flat diagrams; whereas (b) construction-based activities with building blocks are insufficiently modular to account for organic structures or complex mechanisms of target objects.

Design: Evaluating a Discovery-Based Activity for Semiotic Construction

If students could use modular building cubes, I conjectured, they may more successfully perform $2d \leftrightarrow 3d$ conversion: Working in this in-between “2.5d” space, they could learn how 2d orthographic projections encode 3d meanings.

Two study participants (11 y/o, female) were presented with a set of orthographic projection drawings and plastic construction cubes. They were tasked to create an unseen 3d solid (Fig. 1) from a set of orthographic projections (Fig. 2) using plastic cubes and other building materials.



Fig. 1: Target analog 3d solid.

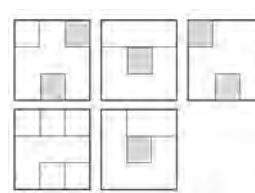


Fig. 2. orthographic projections.

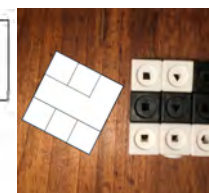


Fig. 3. Flat build of one 2d image.

To structure the guided interview, a set of three *situated intermediary learning objectives* (SILOs; Chase & Abrahamson, 2015) was defined, which the participant would need to meet to show full understanding of the activity: (1) representing physical units in images; (2) continuity of unobstructed faces; and (3) relative depth position of surfaces.

The 2 girls were asked to describe the drawings (Fig. 2). Treating these images as 2d, they cited a maze or a top-down view of a bedroom. Tasked to represent this single card, using the cubes, the girls both succeeded in recreating the figural partitions by using different colored cubes (Fig. 3). However, when asked to make a 3d model from the *set* of images, they faced difficulties.

Qualitative data analysis suggested that the drawings could be theorized as signs, whose normative meanings are not self-evident but, instead, are cultural conventions that are mediated through explicit instruction or via participating in the social enactment of this cultural practice. In particular, the figural features of offset-planes and through-holes did not bear for the participants conventional meanings as construction directives, perhaps because the participants did not eventually have opportunities to witness how the 2d projections had been created from the 3d objects they were to represent (Dutton, 2018).

Conclusions

STEM representations are semiotic structures. Their meanings may not be self-explanatory but, rather, may need to be developed. Identifying which features of a representation are obscure could help locating where learners need more support.

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Monsters, Chromosomes, and Zygotes, Oh My! A Playful Design for Genetics

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Objective: Creating a Learning Resource for Understanding Genetic Inheritance

With the advent of modern tools for genome editing and DNA sequencing, a foundation in genetics is fundamental to understanding human health and DNA-editing ethics. Students should become more familiar with biological mechanisms determining inheritance, namely, how genetics affects organisms' properties and characteristics. An accessible activity is needed for young children to form a normative understanding of DNA and how it is transferred from parents to children.

Background: On the Shortcomings of Experimental and Piecemeal Approaches

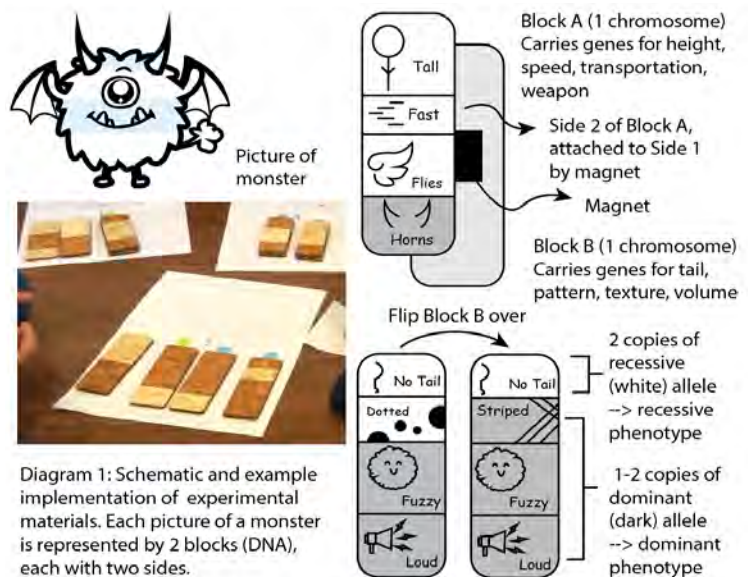
Common representations of genetics employ arbitrary symbols that do not evoke the objects they are to signify. Moreover, genetics curriculum is taught piecemeal, impeding a sense of coherence and purpose. As a result, students often misunderstand the contents, for example, they have trouble connecting the concepts of Punnett Squares and meiosis. Worse, genetics units treat separately the topics "probability of inheritance" and "meiosis," and so students do not realize how these concepts relate.

Previous solutions have explored various ways of making genetics more concrete. Researchers have used card games (Bierema & Schwartz, 2016) or coin flips (Satterthwait, 2019) to help children understand the role of randomness in inheritance by running their own experiments. Others have developed more realistic, 3D models of meiosis and mitosis (Elangovan, 2017) to help children understand biological processes without focusing on probability. However, these solutions still model meiosis and probability separately, whereas, in fact, the probability of inheritance is a consequence of the meiosis process. Interactive computer games let children breed dragons to see how chromosomal genes interact to create offspring (McElroy-Brown & Reichsman 2019). The simulation models inheritance randomness, but it does not illuminate the trait-inheritance likelihood.

Design: Embedding Rules of Inheritance Within Educational Tools – Pilot Study Results

A model of inheritance, I conjecture, should integrate randomness into its structure and function. In this design, children investigate monsters' inherited genotype and resulting phenotypes. Simplified genetic information is displayed on wooden blocks delineating chromosomes (see Diagram 1). The magnetic strips on the blocks encourage users to connect blocks in pairs, modeling organisms' paired chromosomes. By dis/connecting different blocks, users could create new monsters. They could also combine the blocks of two monsters under specified restrictions to create the DNA of a new baby monster and inspect how genetic information passes from parents to children.

Each gene is represented by two opposing alleles (i.e. tail/no-tail), with the dark region symbolizing dominance. Each monster's physical appearance was determined by the descriptors on its blocks, which was to encourage users to explore how the blocks related to the monster. In a pilot study (n=3 – 7, 12, & 14 y/o), users' capacity to predict a monster's phenotype and trait likelihoods hinged on the facilitator's effectiveness in explaining the meaning of the symbols that encode the genotype information.



Conclusions

Whereas educational design have well-defined learning goals, children bring idiosyncratic meanings to their interactions with the educational resources. Embedding interaction constraints into the resources could steer students toward these goals.

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Linear Algebra Conceptions as Movement and Perception in Motor-Control Tasks

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Objective: Addressing Difficulties That Novices Face When Learning Linear Algebra

Linear algebra unifies and formalizes methods for solving linear problems in a variety of domains (e.g., functional analysis and geometry). However, these advantages of the formal theory in terms of generalization and simplification are evident only to experts. For novices, linear algebra brings with it a number of difficulties, including the “obstacle of formalism” related to a heavy emphasis on logical expositions and formal definitions, the challenges associated with navigating different registers and representational systems, and prevalent tendency to prefer procedural over conceptual approaches (Dorier & Sierpinska, 2001). These difficulties motivate the development and evaluation of new instructional approaches.

Background: Using Dynamic Mathematics Environments to Introduce Linear Algebra Concepts

One type of instructional approach for addressing students’ difficulties in undergraduate linear algebra courses leverages the subject’s affinity with geometric representations by using dynamic geometry software. However, previous work on this approach (Gol Tabaghi & Sinclair, 2013; Sierpinska et al., 1999) does not entirely escape symbolic representations’ ontological imperialism (i.e., ignoring intuitive *know-how*’s conceptual potentials, Bamberger & diSessa, 2003); and does not fully embrace these environments’ visual–kinesthetic affordances as fundamental starting points for mathematical inquiry.

Design: Creating Motor-Control Problems Whose Sensorimotor Solutions Anticipate Concepts

Departing from previous approaches, the present design project draws on embodied design (Abrahamson, 2009), a pedagogical framework for creating and evaluating dynamic mathematics environments centered on motor-control tasks. Using the enactive approach to cognitive science (Varela et al., 1991) as a guiding perspective, embodied-design activities seek to ground disciplinary concepts and representations in perceptual solutions to motor-control problems. Figure 1 shows part of the present design: participants are tasked with turning green the draggable Vector u , and to find all areas in the plane corresponding to a green u . As it turns out, u turns green whenever it aligns with its linearly transformed image, $T(u)$. Visual and kinesthetic explorations elicit attentional anchors (e.g., two green lines corresponding to the eigenvectors of T) to coordinate the



Figure 1: Eigenvector design; Vector u turns green whenever it aligns with its linearly transformed image $T(u)$, leaving a trace of eigenvectors.

enactment of “conceptual choreographies” (e.g., moving u along the lines); these, in turn, make salient latent relational features of the virtual environment (e.g., the ratio of u and $T(u)$ is invariant along a green line), thus anticipating normative notions, such as eigenvectors and eigenvalues, which later become elaborated through further discourse and representation.

The above task is part of a sequence of activities, implemented in Geogebra, that do not require prior experience with linear algebra. In another task from this sequence (see Figure 2), participants scale Vectors v and w using Sliders a and b to make their linear combination $av+bw$ congruent with pre-given Vector u . One intended takeaway is that any Vector u can be reproduced by $av+bw$, as long as v and w are not collinear. Such insights anticipate the disciplinary notion of span. We look forward to re-implementing this task as bimanual.

Figure 2: Linear combination design

Results and Conclusions

Tasks such as those described above were implemented as part of a semi-structured clinical interview with a single volunteering participant who self-identified as unfamiliar with the targeted mathematical content. Microgenetic analysis of her multimodal behaviors suggested that pre-symbolic notions relevant for conceptual learning in linear algebra can be indirectly fostered through visual and kinesthetic engagement with dynamic mathematics environments, without *a priori* introduction of formal definitions. The analysis also highlighted the epistemic role that prior experience with Cartesian coordinates can play with respect to the conceptual learning of linear combinations and related notions.

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Putting a Stamp on Geometry of the Solid: Constructing Nets from 3D Objects

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Objective: Create Opportunities for Direct Mappings Between 3D Objects and Their Nets

Children, particularly younger children, experience difficulty imagining the process of folding and unfolding geometric nets and relating them to images of their corresponding 3D objects (Piaget, 2007). This project aimed to support students' spatial reasoning about 3D objects by enabling them to enact direct physical coordination between geometrical solids and their nets.

Background: Cognitive Constraints on Geometry Learning

Whereas young children reason well about piecemeal elements of 3D objects, they often struggle to understand the spatial relation of these elements (Piaget, 2007). Later in life, children find it difficult to transform 3D objects into their 2D fold-out planes (Cohen, 2003). In turn, transforming 2D diagrams into 3D objects requires geometrical literacy (Herbst et al., 2017).

Design: Re-Enacting Nets Through Clay Stamping – Results From a Pilot Study

Two activities were designed for the purpose of teaching students about nets and their relations to 3D objects: (1) In “clay stamping,” students create a net by impressing and rolling 3D objects on sheets of modeling clay. A cube, square pyramid, tetrahedron, and rectangular prism were 3D-printed (Fig. 1). Each solid had raised edges as well as embossed shapes on each side, to facilitate 2D \leftrightarrow 3D mapping. Participants then cut out the clay nets to reconstruct the 3D shape. They were encouraged to create multiple versions of nets and compare their constructability. Later, they were shown net printouts, where some were foils (that did not fold into closed solids), and were asked to predict whether or not the net was foldable. Next, they guessed which 3D objects each net would fold into; (2) In “net folding” (cf. Burte et al., 2017), students were shown net print-outs and asked to predict what 3D shape the net would fold into. They tested their hypotheses with a foldable paper net (Fig. 2). This activity served as a follow-up interview.



Figure 1: 3D-printed geometrical solids (left); trace of 3D solid roll-stamped onto a clay sheet (center); Students roll-imprint the solid's faces onto a clay sheet, creating a net (right).

Study participants (3 x 9 y/o, 1 x 11 y/o; Fig. 1) attended mostly to an object's base in reasoning about its net folding. Challenging items included angular and/or multiple folds. Participants were most familiar with the net of a cube but struggled to interpret nets of less uniform or more varied objects such as pyramids. Participants cited an object's predicted stability as the deciding factor both in selecting the object's prospective base and in determining a net's foldability.

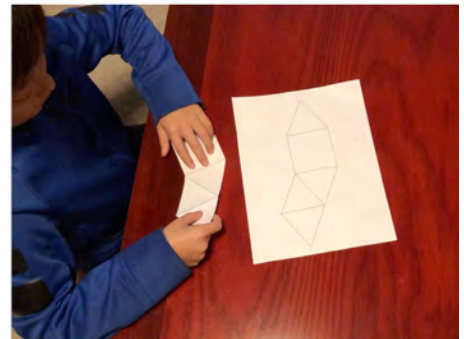


Figure 2: Student tests his hypotheses for the foldability of a given net.

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Conclusions

Enacting 2D \leftrightarrow 3D manual mapping between representations of geometrical objects appears to create productive opportunities for geometrical investigation. Generating nets 3D \rightarrow 2D illuminates the semiotic significance of nets as representations of 3D objects, thus demystifying the operational meanings of nets' diagrammatic features (cf. Dutton, 2018). Building nets 2D \rightarrow 3D in turn creates opportunities to encounter and overcome conceptual impasses via inventing useful strategies and language.

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Mathematical Reasoning as Sensory Regulation: The Balance Number Line

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Objective: Making Mathematics Accessible to Learners with Sensory Processing Differences

Learners on the Autism Spectrum, and many with Attentional Deficit Hyperactivity Disorder, show a heightened need for sensory regulatory movements, such as fidgeting, rocking, flapping, and pacing (Little, Tomcheck, & Dunn, 2018). This design sets forth to make such movements a resource for mathematics learning.

Background: Sensory Regulation

Common sensory interventions include Sensory Integration therapy and tools to accommodate a child's sensory diet in the classroom (balance boards, weighted vests, and fidgets). These interventions remain siloed from curriculum despite evidence that sensory processing impacts academic learning (Ashburner, Ziviani, & Rodger, 2008). Indeed, sensory regulation is not typically considered in the design of math learning designs, yielding potential conflicts. For example, it is difficult to rock side to side while moving one's hands along a vertical number line (cf. Abrahamson & Trninic, 2015). Further, insofar as embodied cognition theory (Varela, Thompson, & Rosch, 1991) obtains, math learning is intrinsically sensorimotor. This provides serious grounds to *query whether movement for regulation and movement for learning are truly distinct processes*.

A latent resource in math instruction is active leveraging of vestibular input to attune learning activities to students' sensory profiles. The vestibular system, which provides feedback to the body about balance, acceleration, and orientation, has been implicated in cognitive performance (Hitier, Besnard, & Smith, 2014). This design's central conjecture is that the integration of vestibular-activating sensory tools with learning designs will improve their efficacy.

Design: The Balance Number Line – Build and Pilot Study Results

The Balance Number Line directly incorporates vestibular–stimulatory movement *as a part of* movement for learning. It does so by making rocking on a balance board central to a series of exploratory and goal-oriented mathematics learning tasks.

The board constitutes a restructuration (Wilensky & Papert, 2000) of the number line that establishes *negative numbers as the equilibrating counterpoint to their positive counterpart*. Learners sit on a balance board and slide their hands along a wall-mounted number line. Their movements cause shifts in the board's balance, providing stimulation to the vestibular system that serves as informative feedback about the placement of their hands (for example, -3 and 3 are experienced as being in balance, while -3 and 4 would be experienced as a slight lean to the right). This design aims to build upon learners' natural engagement with stimulatory behavior and make this a resource for conceptual learning and understanding.

Preliminary pilot findings (13 y/o male, ASD) revealed a hybrid role for sensory regulatory movements, such as rocking. These movements served: (a) a sensory regulation function; as well as (b) to explore and express mathematical concepts. Their frequency and intensity dropped during explicit movement tasks and increased between them. This pattern sustains two potential hypotheses: (1) movement tasks interfere with sensory regulation; and (2) learning movements are themselves sensory regulatory in nature.



Figure 1: The Balance Number Board. The learner sits on the balance board and moves their hands along the central dotted line. Arrows are used to discuss, plan, and document movements.

Conclusions

As the spread of embodied-cognition theory and the proliferation of educational technology shift educational practice, the sensorimotor experience of learning is changing. This shift stands to exacerbate or alleviate extant barriers for learners with sensory processing differences. The key lies in how well sensory regulatory needs are understood and incorporated into learning design. This project exemplifies SpEED: special–education embodied design for teaching and learning (Tancredi et al., 2020).

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A Transparent Environment for Learning Programming

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Objective: Helping Post-Adolescents Learn Programming

The ability to program computational systems is a widely-if-contentiously-recognized skill clearly useful to anyone working in a STEM discipline, but also useful to many working in adjacent fields. Current approaches to teaching programming are targeted to students with a strong math and logic background; for others, new approaches are needed.

Background: Approaches to Understanding Computer Interpretation of Code

Learners of programming face two primary technical challenges: The first, typically, is developing a *notional machine* (du Boulay, 1986)—a mental model used to understand how the computer interprets code. In developing this model, students learn basic syntax and logical structures, like loops and conditionals, as well as facts like “variables are evaluated

before use.” The second challenge is developing a library of *canned solutions* (Soloway, 1986) to common programming problems, for example, how to use a for-loop to identify the largest item in an array. Many curricula ask learners to perform executions of code by hand, answering, “How would the computer run this code?”—a proven way to develop a notional machine (Nelson, 2017). A number of software tools help students develop notional machines through visualizations, using a GUI, of the underlying processes of the computer evaluating code step-by-step, including PythonTutor (Guo, 2013). Few curricula address Soloway’s canned solutions.



Note the yellow dashed-border variable values—these update as the program runs and the underlying variable’s value changes. Note also the green “evaluation in progress” box that shows how the original complex expression `ellipse(30 + (20 * a), 30 + (20 * b), 15, 15)` is evaluated into `ellipse(30, 170, 15, 15)` before the `ellipse` command is run.

Design: Rudy—An Overlay Showing Call Stack, Variable Values, and Expression Evaluation

In contrast to prior work, Rudy makes the evaluation of individual expressions and subexpressions visible and aims to expose as much of the interpreter’s internal state as possible, to help learners develop their notional machines. None of the prior systems illustrate the execution of sub-line expression evaluation, nor do they apply well-known visual design principles, such as visual locality, thus adding confusion. Using Rudy, in contrast, novice programmers can observe changes to their variables inline with the code itself, shown exactly where those variables are defined in the code. Rudy also allows slow evaluation and shows how new variables get allocated and set for function calls. By displaying the inner state and placing all of this state as an overlay over the associated parts of the code, Rudy provides a visual template for a notional machine. To evaluate Rudy, I recorded two task-based semi-structured clinical interviews, in the form of a 90-minute curriculum designed with the tool in mind, with two participants from the neighborhood who had limited programming experience. I coded this data by looking for evidence of the development of participants’ notional machines, and constructing a taxonomy of these changes.

Conclusions

Through analyzing my interviews, I discovered that Rudy helped my participants develop their notional machines to understand a few major concepts: subexpression evaluation, the relationship between variable names and meaning, and nested looping. I also discovered that I, as teacher/interviewer, was directly guiding students using my own internal set of canned solutions—and Rudy offered little support. Future versions of Rudy-the-tool and Rudy-the-curriculum should focus on providing support for students developing their library of canned solutions.

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Teaching Relational Concept Vocabulary to Children Using AAC

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Objective: Teach Relational Concept Vocab. to Children with Complex Communication Needs

The ability to communicate relational concepts is critical for academic success and social participation in and out of the classroom. Effective pedagogical and therapeutic strategies for teaching relational concept vocabulary to children who rely on aided communication systems are lacking.

Background: Relational Vocabulary Among Users of AAC

Relational reasoning is central to human cognition and learning. Therefore, the lexical terms used to describe relations are critical to a language user's vocabulary. Children with complex motor-speech impairments who communicate via Augmentative and Alternative Communication (AAC) show more delays in using relational vocabulary compared to other word types. Aided AAC is an umbrella term for communication systems that utilize external artifacts, like alphabet boards, pictures, or speech-generating technology (Rispoli et al., 2010). Relational concept (RC) words are concerned with location, dimension, position, movement, quantity, presence, and sequence and are important for academic success and cognitive development. Research documenting the use of RCs among children using AAC is limited, but studies have found that users of AAC struggle to use spatial and temporal words when giving directions. It is hypothesized that the development of relational concept vocabulary among this population may be negatively affected by restricted locomotion and mobility, resulting in impoverished opportunities to experience active exploration of objects (Stadskleiv et al., 2018).

Design: Peer-Assisted Construction through Barrier Games

Action-related accounts of language, which are grounded in embodied cognition, suggest that meaning is derived from the biomechanical nature of bodies and perceptual systems (Glenberg & Kaschak, 2002). Construction play creates opportunities for sensorimotor engagement leading to discovery about the physical world, concept formation, and word learning (Ferrara et al., 2011; Piaget, 1962; Stadskleiv et al., 2018).

In the current project, I developed and pilot-tested a pedagogical tool for teaching RC vocabulary to children with mobility impairments using AAC, by engaging them in construction-style activity. The activity, which includes a set of novel materials and photographed arrangements (Figure 1 right), is designed as a set of "barrier games" (Figure 1 left), where the child participant uses their AAC system to direct a partner in recreating a series of arrangements designed to elicit dynamically shifting relational judgments. The partner optimizes for learning by negotiating meanings and soliciting repairs.

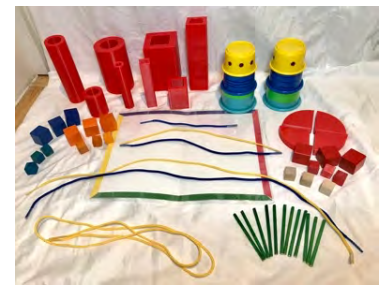


Figure 1: The child-participant attempts to direct the facilitator to recreate a construction depicted in photograph that is outside of the facilitator's view (arrow) pointing to photograph in a box), using the materials available.

Conclusions

Pilot testing on adults without prior AAC exposure garnered promising findings. Pilot participants demonstrated increased speed and fluency in producing relational concept words and formed longer utterances on an AAC system. Analysis of pilot data also revealed a potentially significant sensorimotor-attentional process, relational pivots. A *relational pivot*, I propose, is an individual's shift in perceptual attention toward a focal object to consider its properties in relation to a different aspect or feature of the environment. Relational pivots are stimulated spontaneously in formulating or repairing communication in the course of socially mediated goal-directed activity, such as in accomplishing collaborative socio-linguistic tasks that include distributed joint action. Relational pivots constitute an ontological innovation of this design project and will influence subsequent design iterations and data analysis. I will also keep evaluating this construct in light of cognitive science theory.

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Sense and Sensemaking: On Sensory Modalities and Constructivist Pedagogy

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Objective: Improving Conceptual Understanding of Scientific Phenomena

Per constructivist pedagogy, students' informal experience of a phenomenon is vital for learning it conceptually. Yet, some scientific phenomena are not readily come by in everyday life. Educational designers respond by creating dedicated resources to occasion opportunities for students to ground their formal learning in informal interaction.

Background: Instructionist vs. Constructivist Pedagogy for Teaching Rotational Inertia

Rotational motion is different from linear motion. Whereas students arrive with rich intuitions about linear motion, they bear scant intuitions for rotational motion (Mulhayatiah et al., 2018), specifically for rotational inertia, the resistance of objects to rotation. In response, current pedagogical strategies for teaching rotational inertia rely heavily on simulations, diagrams, and formulas to support students' conceptualizations. This "formalism first" (Nathan, 2012) pedagogy robs students of opportunities to develop their own understanding of the principles of rotational motion through direct and unmediated sensory experiences.

Some researchers break this barrier by allowing students to explore concepts of rotational motion empirically: the researchers ask students to manipulate a rotating body and then visually observe the effects of such manipulations on the inertia of the rotating body (Mulhayatiah et al., 2018; Özdemir & Erol, 2010). This activity is more consistent with constructivist pedagogical approaches, as the students are experiencing the effects of manipulating variables, specifically, the mass and radius of rotating objects, on the objects' rotational motion. What is unknown, however, is *which sensory modalities may contribute to a rich experiential understanding of rotational motion*

Design: Experiencing Rotational Inertia

Three volunteering college students participated individually in a task-based semi-structured clinical interview designed to investigate the multisensory experience of rotational motion. They were provided rotating tops with features for adjusting the variables of mass, radius, and distribution of mass across the radius (see Fig. 1). Materials included a plastic top, mounted cardboard discs of differing radii, and Play-Doh, which served as the variable mass. Participants were asked to manipulate the top's radius and mass and then monitor the top's rotation.

Note that the top rotates too fast for the eye to track and compare changes in rotation velocity (the dependent variable). Unexpectedly,

all participants spontaneously gauged this rotation by gently pinching the top's handle in their fingertips, as it spun. Where the eye fails to detect change in velocity as a visual sensation, the fingertips detect it as tactile sensation. Through thus directly feeling the rotating top, students experienced firsthand the effects of manipulating the top's variables on changes in its rotational inertia. Thus, students were able to physically *experience* the resistance of the top (i.e. rotational inertia) rather than rely on symbolic measures of this phenomenon. They felt the effect.

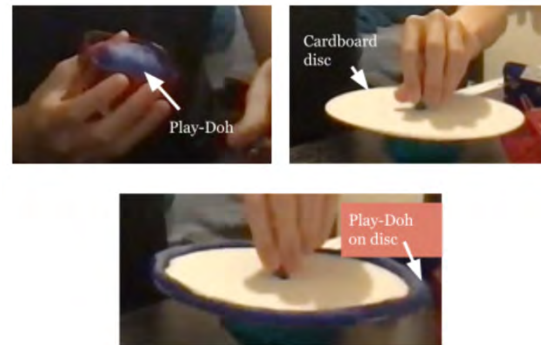


Figure 1: Material resources in a design for rotational motion. Adhesive Play-Doh enabled manipulating mass distribution.

Conclusions

Educational resources supporting conceptual learning of scientific phenomena may be improved through increasing the set of sensory modalities registering the phenomenon. Richer multimodal perceptions of scientific phenomena may facilitate more robust connections between real-world phenomena and the symbolic formulas that purport to model the phenomena. Diversifying sensory experience of science could also cater to students of sensory diversity.

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Breaking Functional Fixedness: Creative Divergent Thinking in Incongruous Contexts

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Objective: Fostering Young Adults' Creativity by Removing Functional Fixedness

This design-based research study aims to provide a heuristic for young adults to overcome the functional fixedness they typically experience with familiar artifacts and, instead, to foster creative divergent thinking with these artifacts as resources.

Background: The Formation and Undoing of Functional Fixedness

Functional fixedness is a cognitive bias that limits a person to use an object only for its typical function, hindering uses of its potential atypical functions (Duncker, 1945). The effect becomes salient as people age (German, 2000) and can be an obstacle to creativity (Rawlinson, 1981). *Divergent thinking* requires people to generate ideas that defy typical thought ruts. It is a crucial process in creative thinking (Guilford, 1984).

When seeing an everyday object in its congruous context, where it typically fulfils its designed function, people tend to perceive its primary affordance. The construct of *affordance* was first coined by Gibson (1966) as “what the environment offers the individual” and later adapted by Heft (1989) as “relative to what an individual can do.” The congruous context reinforces people’s association between the object’s primary affordance and the context’s corresponding affordance. Functional fixedness ensues (Fig. 1). Putting an everyday object in an incongruous context, however, may weaken the association, thus dampening functional fixedness. By highlighting an object’s secondary affordances in an incongruous context, we could boost creative divergent thinking. This exploratory study evaluated the hypothesis empirically.

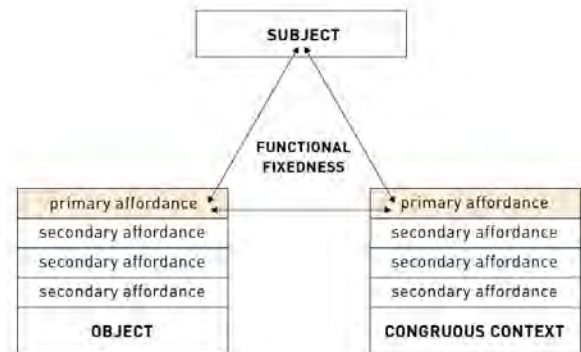


Figure 1: Functional fixedness

Design and Evaluation: Divergent Thinking in Incongruous Scenes

Three volunteering college students participated individually in an experimental intervention designed to alleviate functional fixedness. They were given three everyday objects: a letter-size sheet of paper, a paper cutter, and a cutting mat (see Fig. 2). They were invited to stand in front of a wall projection showing a series of moving images incongruous to the given objects. In each scene, they were asked to name or mime functions of each object or any combination of objects. Through guided post-intervention reflections, participants became aware of their functional fixedness and how they overcame it. The heuristic of imagining an object-specific incongruous scene may remain for the participants as a residual effect for future encounters.

Results and Conclusions

Working in the incongruous context, all participants generated alternative functions for the objects. Qualitative analysis implicated three features of the context as either enhancing or impeding the participants’ creative divergent thinking that overcame the functional fixedness:

1. The richness of the context suggests many affordances for object application. Affordances that cannot be associated with the objects’ primary affordance are especially effective.
2. A context’s ambiguity triggers multiple affordances that enhances creative divergent thinking.
3. Negative visceral level of responses caused by an aversive context will hinder perception of more affordances. While removing functional fixedness, it may impede creative divergent thinking.

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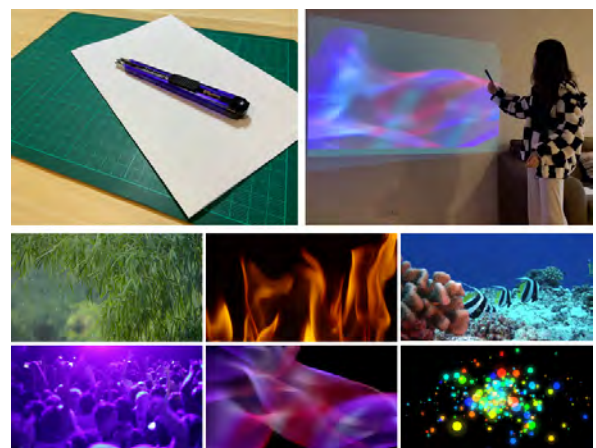


Figure 2: Top-left: Three focal objects. Top-right: Interaction in an object-relative incongruous context. Below: 6 dynamic object-specific incongruous scenes.

Conversations with Clay: Experiencing Acceleration Through Tactile Modeling

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Objective: Providing a Medium for Transmodal Exploration of Kinematic Perception

Students' haptic-tactile engagement in expressing their perception of scientific phenomena may surface tacit facets of their experience. Thus concretizing tacit facets of perception in material form displays student phenomenology for all stakeholders in the learning space—peers, teachers, researchers, and designers—to enhance pedagogical and research opportunities.

Background: Multimodal Learning and Manipulatives

When students experience formal demonstrations of kinematic phenomena, they participate through many sensory modalities, not only sight. However, current educational resources generally do not leverage this multimodal participation in a robust way. Asked to “show one’s work,” one often shows mathematical symbols that document would-be steps that have led to an eventual solution. Explorations, stumblings, and intuitions, though, which are difficult to convey in this form, are lost (Lemke, 2003). Gestures and mental grasping, too (e.g., metaphor), are put aside in favor of formal symbolism. Thus, multimodal pre-conceptual substance, critical for problem-solving processes, mostly goes undocumented (Petitmengin, 2007).

Hands-on approaches to science education often involve using manipulatives to model kinematic phenomena, such as the acceleration of a car rolling down a ramp. However, these approaches do too little to highlight the richness of individual perceptual phenomenology and afford little opportunity for expressing one’s sense-making over time, especially across modalities. My research effort seeks to support students in attuning to and expressing the gestalt of their perceptual phenomenological experience across modalities. This is done through clay, a medium with rich tactile affordances, to surface learners’ inner gestures to enable a transmodal expression of the felt sense of visually observed kinematic phenomena.

Design: Contemplative-Affective Metarepresentational Modeling Activity

“[T]he 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). Accordingly, by applying enactivist (Varela et al., 1991), material-engagement (Malafouris, 2020), and semiotic-cultural theories (Radford, 2003), an activity was designed to facilitate an attuning to one’s felt sense of perception as well as provide materials that afford transmodal expression of tacit facets of this experience. By sensorially divorcing the representational medium (haptic-tactile sensation of clay) from the object of inquiry (visual inspection of virtual objects moving on a screen), we may elicit—for students and researchers—the process of forming transmodal semiotic systems.

The design fostered conversations with the materiality of clay. These conversations began by establishing a contemplative-affective space for three adult volunteers that emphasized sensitivity to the tactile-perceptual experience, drawing heavily on work in accessing felt experience and inner gestures (Petitmengin, 2007). Then, clay was used as a transmodal semiotic means of objectification to surface tacit, yet putatively vital, aspects of participants’ felt experience of their visual perception (see Fig. 1). Through clay, participants constructed systems of idiosyncratic metaphor that were tactile in nature, often involving shape, size, and stretch, demonstrating the tactility of vision. Clay supported participants in developing and modulating their semiotic processes, sustaining dynamic phenomenal qualities, as they generalized from action to symbol. Clay, as an expressive medium, served the participants and the researcher as a transmodally observable trajectory of participants’ emerging formalizations.

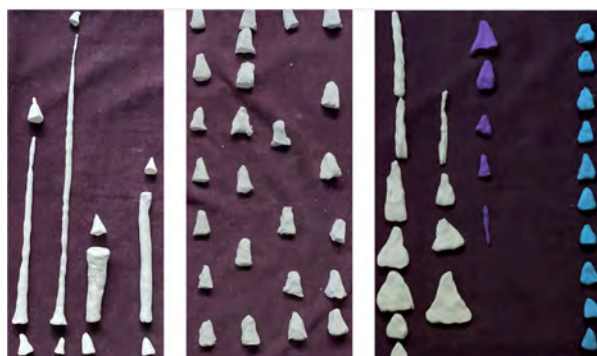


Figure 1: Clay-based metarepresentational modeling of kinematics.

Conclusions

Clay is a valuable medium for exploring the process of sense-making during visual perception of kinematic phenomena. Suggesting a trajectory of understanding via material representation, clay enables important educational insights.

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Walking the Number Line: Enactive Understanding of Integer Arithmetic

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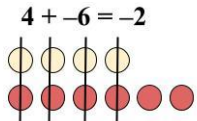
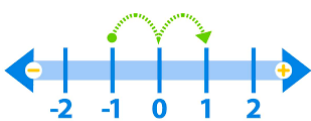
Objective: Improving Number Fluency for All Learners

Basic number sense is a high predictor of children's future mathematical achievement (Lyons & Beilock, 2011). Yet, students often struggle to accurately add and subtract positive and negative integers.

Background: Blocks & Counters vs. Number Lines

Bossé et al. (2017) surveyed the various concrete representations teachers employ to teach integer operations. They found that these representations fall under three categories: (1) isomorphic blocks; (2) colored counters; and (3) number lines:

Table 1. Previous Solutions

Isomorphic Blocks	Colored Counters	Number Lines
		
Pros: helpful manipulatives for adding and subtracting positive integers Cons: cannot accurately portray negative integers	Pros: provide students with clear algorithm for adding and subtracting Cons: tokenizes negative integers as concrete “things;” fails to address polysemy of “-” sign	Pros: represents integers as ratio scale comprising consistent spatial intervals Cons: relies heavily on symbolic notation and iconic signs to represent integers

Children often struggle to adequately use number lines to add and subtract positive and negative integers, possibly because number lines include diagrammatic and iconic signs signifying negative quantities, which are unrealistic entities, that is, they are ungrounded in students' lived experiences and skills. Moreover, the “-” sign ambiguously means both the arithmetic operation “subtract” and the value's negative polarity, an ambiguity exacerbated by symbolic sequences such as “-1 - (-3)”.

Design: Egocentric Walking Number Line & Allocentric Small Number Line

The Walking Number Line was designed to occasion opportunities for students to unambiguously ground negative-integer arithmetic in whole-body enactment. First, students solve basic addition and subtraction problems on a body-scale number line (egocentric experience; Fig. 1). Next, they simulate their full-body actions by manipulating a “mini-me” figure on a desk-scale number line (allocentric orientation; Fig. 2). This bi-perspectival activity sequence may enable students to coordinate the two perspectives (Benally et al., 2022), so that they can ground a normative allocentric use of the standard number line in their egocentric experience walking the body-scale number line. The activity was piloted with 2 pairs of G. 8 low-achieving students.

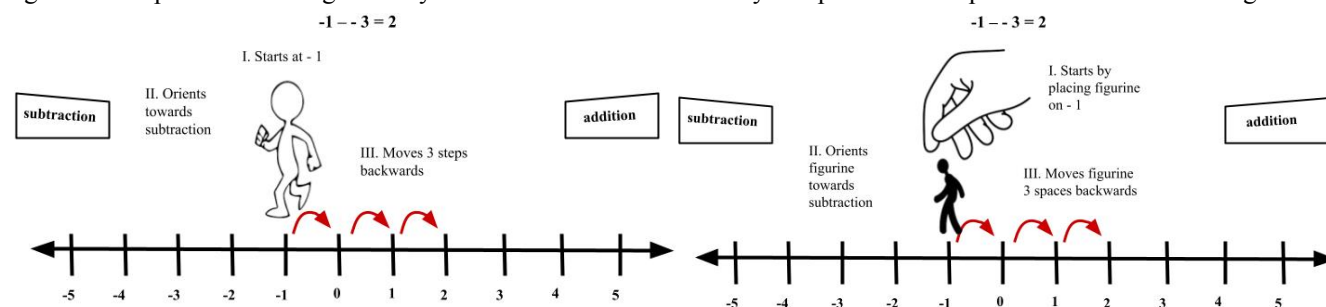


Figure 1. Student walking on the body-scale NL.

Figure 2. Student walking a figurine along a desk-scale NL.

Results and Conclusions

Non-canonical enaction of arithmetic solution procedures elicits and productively disrupts students' mathematically inappropriate solution routines, letting them re-engage with core concepts. Students can learn math concepts by coordinating 1st-person situated enactment of solution procedures and 3rd-person canonical diagrammatic operations on conventional media.

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Grounding Auxiliary Geometrical Constructions as Semiotic Articulation of Tacit Proprioception: The Case of Basic Posture in Balinese Dance

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Objective: Students Will Develop Geometric Reasoning Skills by Grounding Their Proprioceptive Dance Notions in Floor-Based Diagrammatic Resources

GRiD (Geometry Resources in Dance) responds to students' difficulty with geometrical reasoning by creating intuitive-to-formal "bridging tools" for constructing geometric proof (Abrahamson & Wilensky, 2007). GRiD offers semiotic resources to ground explicit proof structures in implicit perceptual structures serving the performance of cultural-historical dance forms.

Background: Recruiting an Ancient "Forgotten Sense" to Understand Geometry

Mathematical proof, a key competency in standards-based curricula (NCTM, 2000), remains an educational challenge (Hsu, 2017). Within geometry, studies implicate students' cognitive difficulty specifically in generating auxiliary lines to investigate latent properties of spatial structures (Palatnik & Dreyfus, 2018). From an embodiment perspective, this design-based research project explores the potential of dance as an activity context for geometry students to practice the ideation of auxiliary lines. Learning to perform movement forms often elicits the spontaneous mental generation of imaginary ecological Gestalts, *attentional anchors* (AA), that tacitly solve motor-coordination problems (Abrahamson & Sánchez-García, 2016). Yet, cultural norms surrounding the movement arts may not include discursive practices for articulating these covert auxiliary forms as overt semiotic constructions. GRiD seeks to capitalize on AA's by optimizing for their semiotic objectification (cf. Radford, 2013).

Design: From Attentional Anchors to Auxiliary Lines—The Case of Tapak Sirang Pada

We introduced a diagrammatic artifact—a gridded floor mat—into a Balinese dance lesson to evaluate whether it would afford the objectification of AA for Tapak Sirang Pada, a basic right-angled foot posture (see Fig. 1). A 10-year-old beginner dancer participated voluntarily in a pilot task-based semi-structured clinical interview. Micro-ethnographic analysis of audio-video data evidenced how the mat both elicited and objectified her tacit AA in proto-geometrical form: she marked a triangle that, she claimed, is her imaginary means of calibrating the posture. Once diagrammed, she could elaborate and extend her embodied argument by bringing to bear geometrical reasoning. Thus, GRiD materials enabled dance-based engagement in geometry discourse by objectifying and augmenting intuitively generated presymbolic notions as external constructions (Kirsh, 2010).

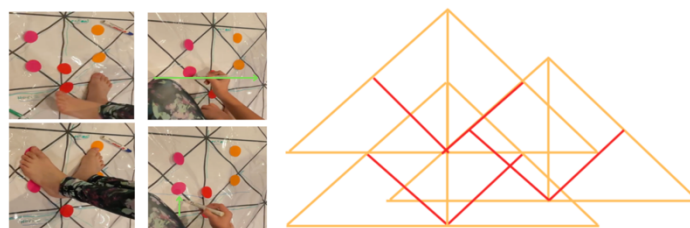


Figure 1. Performing a heel-to-heel right-angled Balinese dance posture serves as a pedagogical context to surface imaginary structures in the form of semiotic elements of geometry practice.

Conclusions

The GRiD project elaborates on the action-based genre of the embodied design framework (Abrahamson, 2014) by way of situating students' semiotic objectification of presymbolic notions within *culturally authentic* fields of promoted action. GRiD begins from an existing cultural-historical practice, Balinese dance, where participants have already developed attentional anchors to perform conventional choreographed forms, e.g., poses and gestures. As such, GRiD demonstrates how formal mathematical discourse can sprout from culturally diverse practices. While GRiD innovates a culturally-historically situated exemplar of embodied design, the project also creates an empirical context for future research into questions of epistemology and axiology pertaining to globalizing embodied mathematics pedagogy: How can we best empower students' cultural identity?

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Bootstrapping Students' Emergent Ideas: Case Study of Students' Guided (Re)Invention of Abstract Math Concepts

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Objective: Help Students Learn Abstract Concepts Through Guided Generalization

The project's purpose is to advance our understanding of how students generalize concepts as well as to advocate for student-centered pedagogies, e.g., inquiry-based learning (Laursen & Rasmussen, 2019) in undergraduate math classrooms.

Background: The RME Framework and the Variation Theory of Learning

Realistic Mathematics Education posits that mathematics education should support students to “reinvent” concepts by modeling experientially real situations (Freudenthal, 1973). Instruction should explicitly tap into students' intuitive, emerging ways of understanding the world (Cobb et al., 2008) and “mathematics is best learned by doing mathematics” (Van den Heuvel-Panhuizen, & Drijvers, 2020, p. 715). Variation Theory guides educators in the strategic selection of examples that optimally balance similarity and difference of features (Kullberg et al., 2017). The project combines these two approaches.

Design: A Hands-On Experiential Learning Sequence Towards Generalizing the Idea of Group

My design for learning about *group*, an Abstract Algebra concept, begins with a simple symbolic example affording intuitive comparison. Next, I add items bearing nuanced differences, to require reflection, conjecturing, and conceptual refinement. Then, a physical example introduces new cognitive challenges transforming a 3-color triangle according to specified rules (see Fig. 1). Students may then “fold back” to simpler examples to grasp the underlying structure (Pirie & Kieren, 1994). Once students have generalized the examples' shared structures (e.g., in table form, see Fig. 2), we formalize an abstract concept and revisit the lessons' earlier examples as special cases.

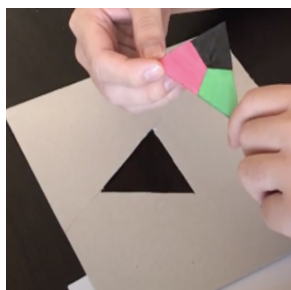


Figure 1: The triangle

	1	2	3	4	5	6
1	1	2	3	4	5	6
2	2	3	1	5	6	4
3	3	1	2	6	4	5
4	4	6	5	1	3	2
5	5	4	6	2	1	3
6	6	5	4	3	2	1

Figure 2: Analysis of the triangle

Research Questions

1. What are students' epistemic grounds for evaluating the logical validity of a mathematical generalization?
2. Can student-generated vocabulary bootstrap dyadic inquiry, and, if so, what is the process of this phenomenon?

Findings: Students' Vocabulary Bootstraps Inquiry; Epistemic Grounds for Generalizing

Analysis of data from a pair of first-year STEM undergraduates led to identifying and operationalizing 9 aspects of their epistemic grounds for evaluating the logical validity of a mathematical generalization: (1) order and coherence of thoughts; (2) embodied manipulation of objects; (3) naïve empiricism; (4) emerging rules; (5) enabling prediction; (6) inferential parity (Abrahamson, 2014); (7) varying conditions and exploring relevant constraints; (8) exhausting all possibilities; and (9) justifying using established observations and reasoning. The study participants spontaneously used their generated vocabulary of “order” to bootstrap their dyadic inquiry. In so doing, they disentangled commonly conflated properties of *commutativity* and *associativity*. The study demonstrated that RME bears fruitful potential for undergraduate STEM education, and that inquiry-based learning is a promising method for undergraduate students to develop agency and learn abstract concepts.

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Project EnAACTicon: Being the Agent of Socialization

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Design Problem: The Absence of a Social Competence Pedagogy for Students Who Use AAC

Social interaction is critical for cognitive development and general well-being. For individuals using augmentative and alternative communication devices (AAC), however, mainstream pedagogical methods do not occasion adequate opportunities to experience and practice dimensions of generalization, maintenance, and validity inherent to unmediated social interaction. Consequently, AAC users are experiencing minimal social participation and increased social isolation.

Design Analysis: Overcoming Sociality Limitations of AAC Through a Design for Joint Action

Popular social competence strategies (e.g., Social Stories and Video Modeling) are formatted as series of independent lessons. These interventions use either a video or a picture book to model appropriate social-communication strategies. However, these lessons position the student in a passive allocentric perspective, with minimal chances to “be” the protagonists or to utilize non-verbal expressive modalities, such as performing pantomime as forms of narrative reenactment. Moreover, AAC iconic symbols for words conveying epistemic or sensory stance (e.g., “know,” “believe,” “think,” “feel”) can be non-intuitive and, thus, cognitively taxing, in part because they, too, are allocentric projections (Bialystok, 1986).

Merleau-Ponty (1964) introduced the notion of *intercorporeity* to depict social interaction as bodily coupling in a mutual action-perception system (“in-synch,” Stadskeiv et al., 2022). Naturally occurring communication is a social function constituted in, through, and for joint action (Melser, 2004). Socially normative opportunities for intercorporeity are, thus, to engage in joint action, enabling each actor “(i) to share representations, (ii) to predict actions, and (iii) to integrate predicted effects of own and other’s actions” (Sebanz et al., 2006, p. 70). When joint action is routinely embedded in social activities, it occasions egocentric agentive experience and multimodal enactment of perceptual, epistemic, and affective notions. Hence, these routine experiences afford the development of social competence (Holdgrafer & et al., 1989).

Design Solution: The EnAACTicon

Project *EnAACTicon* seeks to introduce multimodal first-person communication experiences into AAC architectures by creating material resources supporting joint-action narrative enactment, where users can “be” rather than just “see” a story (cf. Gerofsky, 2011). A design prototype consists of 4 gloves (2 per participant, see Fig. 1, left). Elastic bands connect one’s hand to the partner’s opposite hand. When spontaneous hand movements render the band taut, subsequent action may require “Pushmepullyou” negotiation, such as via non-verbal attuning into repetitive synchronized joint acting (see Fig. 1, right). Interactants maintain their joint action coordinated via dynamic, iterative, and reciprocal micro-adjustments to the location, timing, and thrust of their respective sensorimotor actions. Dyads watch an animated short (Eggleston, 2001) then co-reenact it. Interactants may, thus, shape each other’s perceptions via idiosyncratic expressive action.



Figure 1: Prototype resource. Elastic bands connect the participants’ gloved hands, prompting the coordination of joint action serving distributed multimodal narrating.

To further explore the coordination of egocentric and allocentric perspectives, future participants will then be asked to generate the animated short using a material storyboard. We will thus measure for residual effects of intercorporeity.

Conclusions

Pilot trials of the designed prototype with several verbally normative participant pairs surfaced three effects that collectively suggest the project’s potential: (1) the medium productively constrained individual actions, thus stimulating joint action; (2) participants engaged in whole-body expressivity; and (3) participants negotiated action roles and performance sequencing.

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3D Printed Color-Coded Tracheobronchial Tree for Bronchoscopy Training and Anatomy Learning

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Objective: Teaching Tracheobronchial Anatomy and Spatial Reasoning

Bronchoscopy is a critical skill in pulmonary and critical care medicine. Understanding tracheobronchial anatomy and spatial reasoning is fundamental to performing the procedure optimally. Current approaches are unsatisfactory.

Background: Current State and Gaps of Tracheobronchial Anatomy Training

Despite extensive training, learning tracheobronchial anatomy via bronchoscopy remains challenging. One study of pulmonary fellows showed a 71% success rate in correctly identifying accessing the target airway on command (Crawford & Colt, 2004). Interestingly, there was minimal correlation between number of bronchoscopies performed and accuracy. Training in bronchoscopy remains highly variable amongst pulmonary training programs but many still employ volume-based competency despite recommendations to favor simulation (Ernst et al., 2015).

Current options for bronchoscopy simulation include commercial manikins which offer a physical medium for training but only anatomic approximation. In fact, one study of upper airway manikins demonstrated poor replication of true human anatomy (Schalk et al., 2015). Virtual reality simulators allow for manipulation of scenario, physiologic realism, and accurate anatomy but are incredibly costly and have limited haptic feedback (Deutsch et al., 2009). 3D printing (3DP) has garnered increased interest in generating low-cost bronchoscopy simulators, allowing for representative anatomy and modifiable characteristics (Ho et al., 2019)

Design: 3D Printed Tracheobronchial Model with Color-Coding and Orientation Markers

We created a 3DP tracheobronchial with color-coded airways mapped to a legend, and a printed anterior blue line for orientation (see Figure 1). Egocentric and allocentric spatial reference frames suggest simpler spatial processing in a 3rd person allocentric perspective compared to a 1st person egocentric perspective (Burgess, 2006).

The 3DP model was placed adjacent to the bronchoscopy screen to facilitate coordination of the egocentric bronchoscopy view and allocentric external model view. Our study showed a link between 3DP model learners and using allocentric perspectives to understand the anatomy and airway spatial relationships. These learners also preferentially used the anterior blue line and color coding as ‘attentional anchors’ (Abrahamson & Sánchez-García, 2016) to facilitate learning relationships within the tree and bronchoscopy.

Conclusions

Learning bronchoscopy and endoscopic tracheobronchial anatomy are challenging. We have developed a unique 3DP simulator with embedded cognitive resources to focus on breaking down the barriers by facilitating parallel processing of egocentric and allocentric perspectives.

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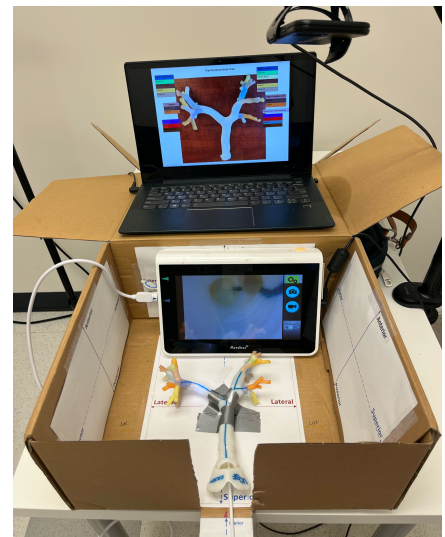


Figure 1. 5th generation 3DP model, showing orientation markers on sides, model and bronchoscope screen adjacent, and legend above. The model has an anterior blue line and color-coded airways.

The Promise of Creative Expression in Research: An Exploration of Visual Arts-Based Methods Within Youth Mental Health Research

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Objective: Exploring Mental Health with Visual, Arts-Based Methods

Forms of visual expression, such as drawing, offer the ability to surface and depict complex thoughts and feelings (Kearney & Hyle, 2004). This project explored whether a brief, visual arts-based drawing activity using familiar drawing tools (e.g., crayons, markers, and colored pencils) to respond to prompts about mental health could: (1) serve as an engaging method for participants to explore and express their knowledge and experience of mental health; (2) stimulate open, honest communication between researcher and participant; and (3) help generate an engaging and positive experience for participants.

Background: Mental Health and Arts-Based Research

Over the last decade, rates of anxiety, depression, and suicidal thoughts among young people in the United States have steadily increased, reaching crisis levels during the COVID-19 pandemic (Ethier & Mermin, 2022). Over 75% of all mental health problems begin by age 24, and 50% have their onset during adolescence, making early intervention and prevention key strategies for addressing youth mental health (YMH) (Woodgate et al., 2021). YMH interventions must embrace more innovative and dynamic approaches that center the lived experiences of young people, are interactive and experiential, and are relevant and developmentally appropriate (Murman et al., 2014). One key point of intervention includes encouraging youth to practice self-expression, openness, and vulnerability about their feelings, thoughts, and experiences (Edelblute et al., 2018). This skill-building opportunity is intended to empower youth to express themselves in a developmentally-appropriate, emotionally safe contexts, as well as challenge stigmatizing language and ideas around mental health (Cheung et al., 2016). Visual arts-based research methods have been found to help create a safe environment for young people to openly and honestly express their thoughts, perspectives, and experiences about difficult or sensitive issues (Cheung et al., 2016). While drawings may be a more common data collection tool today than in the past, only limited research has been reported about the use of this method in promoting youth mental health.

Design: Visual Arts-Based Drawing Activity

My design sought to explore how visual expression via familiar drawing tools would impact the experience of responding to prompts about mental health and wellbeing. Participants were given 2 prompts (I. How are you feeling today?; II. What does “good mental health” feel like to you?). They had 10 minutes to answer each prompt. After responding to each prompt, they were asked a series of questions to gain insight into their image, choice of colors and tools, and experience of doing the activity.



Figure 1. Participant responses to Prompt I (left) and Prompt II (right).

Conclusions

Visual arts-based methods have the potential to shape the depth with which participants communicate their thoughts, feelings, experiences, and ideas about complex, multidimensional concepts, such as mental health. The available drawing tools and structured activity provided an accessible way for participants to process, integrate, and express in abstract, creative, and non-linear ways. Due to limitations in sample size and access to target population, further investigation is needed to determine intervention potential and effectiveness.

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