and get one to experience something new, precisely by creating an otherwise "impossible" situation.

« 8 » What does all this mean for creating learning environments? Must VEs simulate, substitute, and dismiss our embodiment? Not at all: they could afford new spaces and interactions, enrich our existing worlds, and re-embody their users – when designed in a specific way. We need a new hybrid way of pedagogy that captures the good things we *can* get out of online and virtual modes of learning. For instance, our sensorimotor experiences need to be acknowledged when designing such spaces – our bodies are not completely "staying behind," after all. VEs should also let us do impossible things (Cogburn et al. 2018), and let us *play*. We can learn a lot when we are *not* trying to replicate the lived world, but create new play spaces that open up new affordances for action. Priority could be given to creating such virtual affordances, rather than to creating graphics that aim to provide exact reproduction of the lived world. Yet, genuine visual images need not be as important as creating a sense of *agency* or feeling empowered to act – with the kind of freedom to err, and curiosity, that playful spaces allow.

« 9 » To conclude, the designers of online pedagogical environments should recognize the strength of creating a non-identical parallel space that could be used in smart ways, such as a space for playful exploration, and not for serious imitation. Yes, there are restrictions regarding some aspects of our embodiment and sensorimotor interactions in VEs, and maybe these interactions cannot be replaced. So, what if we do not try so hard to replace them, and simply focus on adding new skills to our repertoires? And instead of worrying about "sensorimotor dumbing-down" (§35), why not acknowledge those limitations of VEs, and see what possibilities they can open up for our online pedagogies instead? I hope to have shown that virtual technology has the potential for opening up new, pragmatic ways of learning. This constitutes my optimism.

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Almost in Our Grasp: The (Slow) Digital Return of Multimodal Educational Resources

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> Abstract • Whereas I empathize with Penny's grave concern over current modalist instructional technology – "modalist" in the sense of privileging one modality, predominantly vision, at the expense of all others – I do not quite share his bleak assessment of future offerings. Following some hopefully inspiring words from historical philosophers of education, I showcase the Quad, a haptic–tactile mechatronic device built by three US-based laboratories collaborating to create modally expansive learning tools for classrooms that are inclusive of sensorially diverse students. While the Quad is "digital" in the familiar computational sense, it is at once "digital" in the corporeal sense of evoking the fingers – it reintroduces mutimodal engagement into mathematics learning.

« 1 » A while ago, I was involved in a research study at the University of California San Francisco's Medical School. Robotics surgery was rushing in, and faculty were scrambling to figure out how to train novice surgeons. These faculty were typically senior surgeons, who had spent decades of their career operating hands-on, or, better, hands-*in* patients' bodies; they had then transitioned through laparoscopy surgery eventually to robotics surgery, which they were now teaching. The novice surgeons in residence, on the other hand, had only

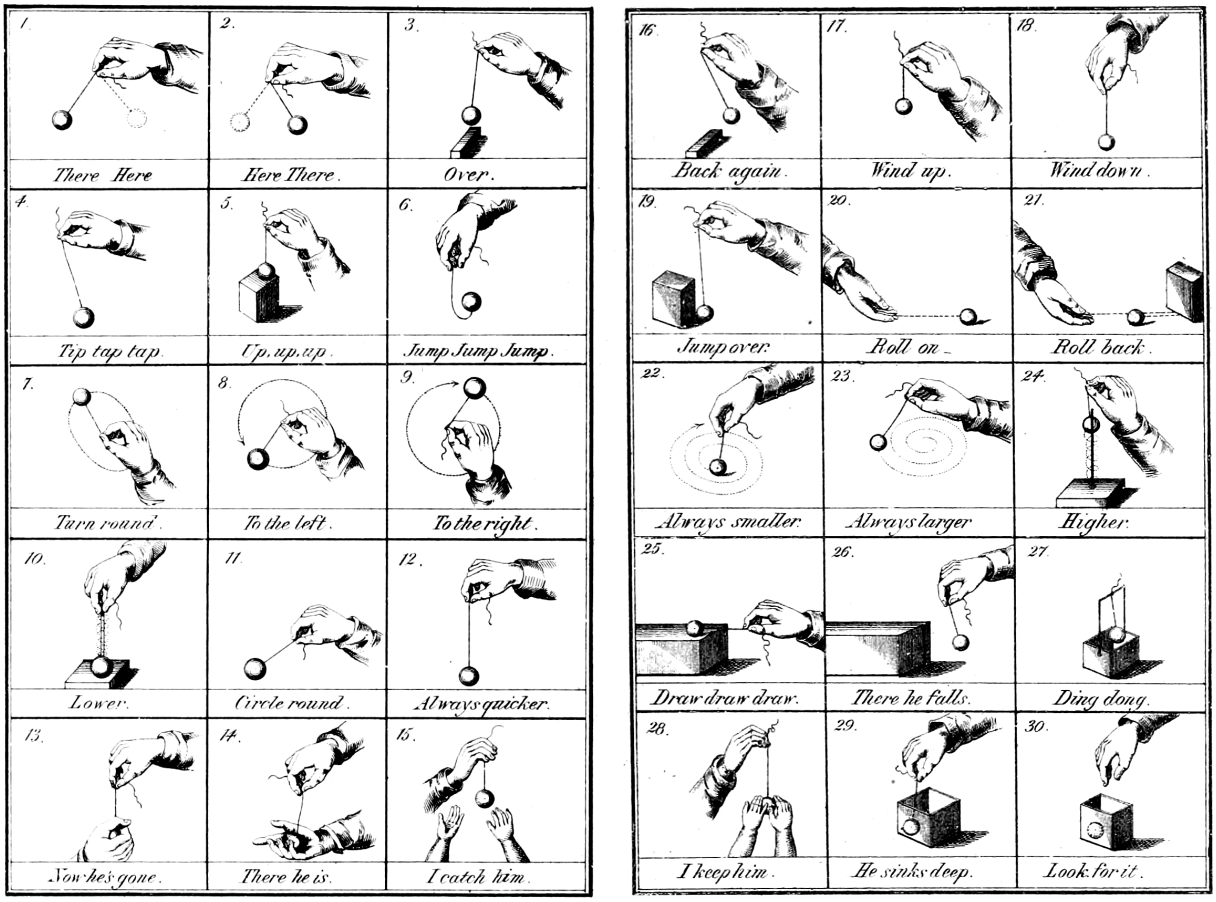

Figure 1 • The yarn ball, Fröbel's Gift 1, with his original recommended activities, from Ronge & Ronge (1858).

a few hours under their belts operating directly on bodies, at least, live human or porcine bodies. I was invited to make sense of a phenomenon that was frustrating the ward's education specialists: The novice surgeons operating robotically kept damaging the human organs they were remote-manipulating – usually of cadavers, fortunately – by stretching tissues beyond their elastic endurance. Why were these able digital natives abusing the delicate organic matter? The hypothesis I put forth was that whereas the attending and novice physicians both saw the same images on the screen, the novices could not experience the affordances of the tissue similarly to how the experts did, because they had never manipulated the tissue directly with a gloved hand – they did not feel what they saw (Green et al. 2018). It turns out that it helps to take your head out of the console – then the attending and novice surgeon can talk about the images they are both seeing and gesture to them (Green et al. 2020), as humans are wont to do (Alač & Hutchins 2004).

« 2 » I tell you this story to signal my resonance with Simon Penny's concerns over phenomenological gaps between multimodal "actions conducted in the world and in purportedly comparable online simulations of such activities" (§2), simulations that "usually fail the test of ecological validity" (§24). Similarly, I concur with Penny's conclusion: "The current challenge is to assess the role of enactive, embodied and situated practices in learning in general […] and in online environments in particular" (§44).

« 3 » As a design-based researcher of teaching and learning, Penny's "current challenge" falls squarely in my bailiwick. Immediately, I ask, has it always been this way? How did this happen? Why did we narrow down the vast ocean of multimodality to the doldrums of ocular straits? To address these questions, we might look back to look forward at the role of manipulation – and I mean full-fledged haptic–tactile–kinesthetic palming, tugging, twisting, and so on – in pedagogical scholarship and practice. Mine is a peculiar domain of cognitive development, mathematics, where it is not *a priori* clear what the *thing* is that one should manipulate, as compared, say, to archeology, botany, or carpentry. This ontological conundrum has stimulated much debate that would go beyond the scope of this commen-

tary (but see Abrahamson, Dutton & Bakker 2021). Touching upon the mathematical domain, though, I will end on a sanguine note by briefly demonstrating the potential contributions of inclusive design to "re-handing" cognitive enskillment.

Looking back

« 4 » Abrahamson, Ryokai & Dimmel (in press) survey the history of digital educational artifacts. Their thesis is that "we're not there yet" – whereas interactive technological devices offer all the known virtues of information and communications technology, such as memory, representation, computation, augmented and virtual reality, and the internet, these human–computer interaction appliances are by and large ocularcentric, having elided the multimodal sensuous body. Consequently, touch-screen-based learning activities suffer from modal paucity to the detriment of the end-user multimodal students. As a historical baseline, the authors look at mechanical resources – "gifts," he called them – that Friedrich Fröbel, an educational visionary, developed for children enrolled in a new type of institution he inaugurated in 1837, which he called a "*Kindergarten*." Figure 1 features thirty proposed activities with Fröbel's Gift 1, the yarn ball.

« 5 » Fröbel's instructional regimen implemented his philosophical-cum-practical thesis on early education, which advocates for the essential role of play, autonomy, craftsmanship, creativity, sociality, and the outdoors in the development of the child's mind, summarized in *The Education of Man* (Fröbel 1895). Norman Brosterman (1997) proposes that interacting with Fröbel's gifts at an early age impacts students' life-long inclinations, as one might discern from the apparent resemblance of childhood and mature artifacts created by Fröbel kindergarten graduates Frank Lloyd Wright, Richard Buckminister Fuller, Piet Mondrian, and many others. Fröbel's conviction that specialized educational artifacts are critical for children's cognitive development may have been nurtured from a West-European zeitgeist. Indeed, already a whole century before Fröbel, in 1762, the philosopher Jean-Jacques Rousseau (1979) had insisted that the eponymous child *Émile* should learn not from symbols but from "the thing itself" (*l'objet même*).

« 6 » Fröbel upgrades Rousseau's Enlightenment argumentation with Romantic leanings toward nature, passion, and self-development. In his 1829 plan for the *Volkserziehungsanstalt* project at Helba, which, alas, was never launched, Fröbel lays out the following paradigm:

> "The institution will be fundamental, inasmuch as in training and instruction it will rest on the foundation from which proceed all genuine knowledge and all genuine practical attainments; it will rest on life itself and on creative effort, on the union and interdependence of *doing* and *thinking*, *representation* and *knowledge*, *art* and *science*. The institution will base its work on the pupil's personal efforts in work and expression, making these, again, the foundation of all genuine knowledge and culture. Joined with thoughtfulness, these efforts become a direct medium of culture; joined with reasoning, they become a direct means of instruction, and thus make of work a true subject of instruction." (Fröbel 1895: 38; supplemental editorial notes composed by W. N. Hailmann, the translator; emphases in the original)

« 7 » One might interpret Fröbel's revolutionary vision of a doing–thinking pedagogy as reversing the ancient Greek conceit of the liberal arts – that is, the intellectual curriculum of privileged free citizens – so as to re-integrate Aristotelian *techne* and *episteme*. Indeed, Richard Parry (2021) expresses a certain frustration in attempting to pin down what Aristotle meant by this pair of constructs, citing apparent inconsistencies across the philosopher's voluminous oeuvre: at times Aristotle speaks of *techne*, the propensity to craft new objects, as inhering *episteme*, knowledge of necessary causation. To my reading, our post-Renaissance conceptualization of science as empirically validated generalized theory and, perhaps, a certain contemporary axiological valorization of theory *versus* practice may impede a historical reading of Aristotle. As any reflective practitioner will attest, professional activity is predicated on bearing implicit theories that surface to the fore of our mind as we deliberate over our actions (Schön 1983). I wish to submit, therefore, that a more humanistic and equitable consideration of *techne* and *episteme* would be not as demarcating identity, occupation, or any socioeconomic demographic but, instead, alluding to a pan-human epistemic mode. Paraphrasing philosopher Gilbert Ryle (1945), I maintain that any *know-how* potentiates *know-that*, which may coalesce into explicit, even verbalized rumination at moments of *breakdown*, when "The environment announces itself afresh" (Heidegger 1962: 105; see also Koschmann, Kuuti & Hickman 1998).[1]

« 8 » Similar ideas would be expressed a century later, in 1916, by philosopher John Dewey:

> "[C]areful inspection of methods which are permanently successful in formal education, whether in arithmetic or learning to read, or studying geography, or learning physics or a foreign language, will reveal that they depend for their efficiency upon the fact that they go back to the type of the situation which causes reflection out of school in ordinary life. They give the pupils something to do, not something to learn; and the doing is of such a nature as to demand thinking, or the intentional noting of connections; learning naturally results." (Dewey 1944: 154)

It goes without saying that Dewey's "doing" is concretely hands-on, not computer-mediated hands-on.

« 9 » We are now looking intently at the hand. The pedagogical oeuvre of educator Maria Montessori is based on manipulating material resources that have been carefully selected and crafted to promote cognitive development. She writes:

> "Human logic says we must distinguish between mental and physical activities, for mental work we must be immobile in a class room and for physical work the mental faculties are not required. It cuts the child in two. When he thinks he may not use his hands, and when he uses his hands his head is not considered. Thus we get men with a head and no body at one time and with a body and no head at another. [….] Yet nature shows that the child cannot think without his hands and that the hands are the instruments of intelligence. Objects must occupy the hands and interest the mind." (Montessori 1967: 252)

1| For further elucidation of differences between the Aristotelian *techne* and *phronesis* in professional practice, see Braude (2017).

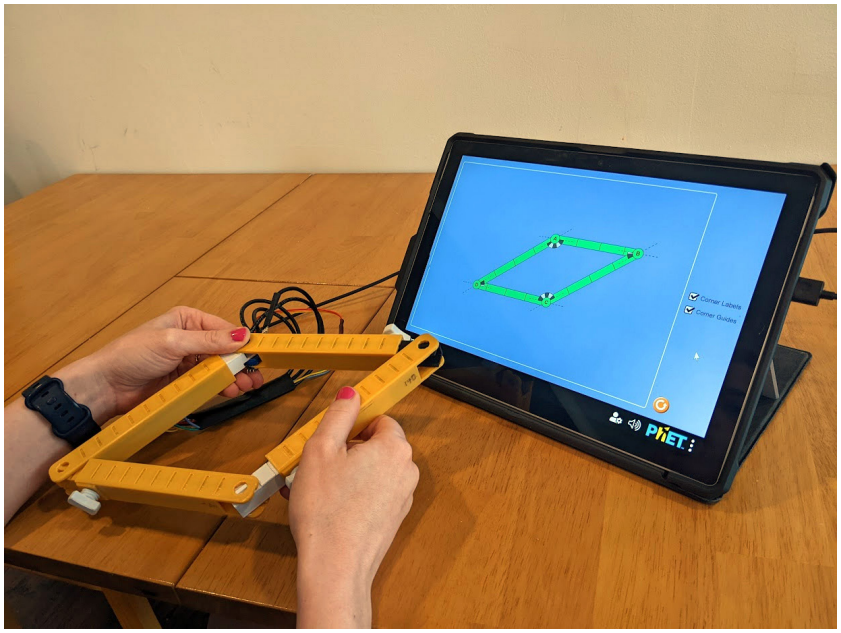

Figure 2 • The digitally connected tangible manipulable quadrilateral: An intermodal technological system for exploring geometric shapes.

« 10 » Where did we go wrong? Sages of the ages implicated the hand – palm, fingers, opposable thumb, and all – as bringing forth knowledge of the world. It is this evolved capacity to bring forth a world through groping, grasping, grabbing, that our species co-opted, some believe, as the epistemic practice of bringing forth mathematical objects (Abrahamson 2021). Notwithstanding, the early waves of digital pedagogy, with their command-line interfaces and, later, graphical user interfaces, were all body snatchers. Even embodied and tangible user interfaces (TUI) can fall short of constituting "technology that is sensitive to the principles of biological cognitive systems" (Glenberg 2006: 271), as I together with Rotem Abdu (Abrahamson & Abdu 2020) exemplify in our critique of common interactive discovery-based learning environments for geometry. Should we just wring our hands?

Looking forward

« 11 » I believe there is hope. Abrahamson, Ryokai & Dimmel (in press) portray 20th-century educational technology as the desert generation waiting to be reincorporated. A current confluence of developments in embodiment theory, TUI technology, and multimodal-learning-analytics methodology (Abrahamson 2019), along with new conceptual perspectives on universal design for learning (Abrahamson et al. 2019), have fostered a line of multi-laboratory collaborative interdisciplinary research that is developing and evaluating mechatronic devices for the inclusive learning of sensorially diverse students.

« 12 » The tangible manipulable quadrilateral ("Quad," Figure 2) combines material and digital interfaces with multiple interaction and information modalities. Visually impaired study participants have responded with great enthusiasm and encouraging performance (Lambert et al. 2022). The Quad's most current build includes embedded motorized actuators that can dynamically transform the shape's edge lengths and vertex angles. When two students are discussing a shape, they can remote-adjust each other's quadrilateral by changing their own, even when the students are remote-conferencing.[2]

« 13 » We are not there yet. However, the darling buds of mechatronic gifts may herald a renewed appreciation for the educational promise of digital technology. It is in our hands.

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2| To learn more about the theoretical unpinnings, technical details, and empirical evaluation of the actuated Quad, see an upcoming article currently under review, "Intermodal learning systems: A flexible, hardware–software framework for inclusive, integrated multimodal educational simulations" by Scott Lambert and colleagues.

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Reduction and Enactment with Digital Images: What Can 0s and 1s Represent?

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> Abstract • I explore whether there are differences in kind between digital images that reproduce things from our lived world and digital images that enact conceptual relationships.

« 1 » In his target article, Simon Penny argues, vividly and convincingly, that the emergency shift to online everything during the Covid-19 global pandemic (a) widened the rift between the "miners" and "gardeners" who steward academia (§6), and (b) brought into relief the urgent need for a "revalorization of embodied, enactive and sensorimotor aspects of pedagogical and research practices" (§44). I read the essay with interest, both as an educational researcher and teacher educator, and also as someone who holds degrees in mathematics and philosophy. My learned, professional life depends, primarily, on symbolic abstraction.

« 2 » Despite my clear involvement with the miners' camp, I raise no objections to the author's characterization of the abstract, reductive, and confining view of our lived world that results from our efforts to conceptualize, analyse, and investigate it. In my work, I have mined the enacted experiences of secondary mathematics teachers using multimedia survey experiments (Dimmel & Herbst 2018, 2020) and designed interactive environments (Dimmel & Pandiscio 2020; Dimmel, Pandiscio & Bock 2021) that exemplify the "sensorimotor dumbing-down" (§35) and multimodal narrowing (ibid) that are part and parcel of digital spaces (§27). Even with my reliance on digital imagery,[1]

1| My work with survey experiments uses digital images of storyboards that feature cartoon renderings of mathematics classrooms as probes to prompt practicing teachers to reflect on their practice. These storyboards, by design, are intended to be simplifications of classroom activity. My work with interactive environments includes digital diagrams, like the examples discussed be-