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Article title: **Body studies in mathematics education: Diverse scales of mattering**

Elizabeth de Freitas & Nathalie Sinclair
Manchester Metropolitan University & Simon Fraser University

l.de-freitas@mmu.ac.uk & **nathsinc@sf.ca**

Abstract: This paper offers a survey of body studies in mathematics education. Building on earlier insights about the 'embodied mind', which focused primarily on individual, intact bodies, we focus on recent work that elaborates bodies as distributed and extended and fully implicated in socio-material ecologies of learning. The aim of this article is to map current trends in this domain, and to articulate some of the current challenges. Because bodies matter differently depending on the research perspective, and because they are studied at multiple scales of mattering (neurological, sensory-gestural, affective, social, institutional, national, etc.), there tends to be disparate insights across the field with little to no cross-fertilization. This paper aims to open up conversations across different theoretical approaches – and scales of mattering - so as to create a more expansive and inclusive agenda for body studies in the field of mathematics education. We have chosen to organise our survey around several themes that seem dominant in the literature, where key theoretical and methodological trends can be discerned. These are: (1) groups, systems, ecologies (2) affect, movement, sensation, (3) language-use and gesture, (4) dis/ability and power, (5) technology, technicity, and tools. We argue that these different approaches need to be in conversation with each other, to think across research contexts, problems and communities, so that new forms of inquiry and new insights can emerge.

Keyword: body; politics; technology; biosocial; disability; post humanism; methodology

1. Introduction

There is a long history of *body studies* in the humanities and social sciences, where attention to the material conditions of human embodiment has shed light on the political, economic and cultural forces that shape lived experience. Much of this work has been fuelled by feminist and race philosophers who have fought valiantly to open up theoretical discussions about the differentiated nature of embodied experiences. These philosophers insist that the socio-cultural construction of concepts such as gender and race cannot ignore the material fact of the body, nor posit is as benign, simply passive to discursive forces (see, for example, Grosz, 2005). Bodies are situated in multiple space-time contexts, each operating according to different material conditions. The body bears the stamp of socio-material constructs such as gender, race, sexuality and dis/ability. Different bodies matter differently, and are produced, positioned and enabled through their engagement in different milieus. Body studies have also emerged from within psychological paradigms as well as the phenomenological tradition, and are linked to perception studies and embodied cognition, such as in the enactivism of Merleau-Ponty (2005), who challenged body-mind dualism. Alongside these developments we have also witnessed the continued production of new biotechnologies and pharmaceutical methods to modify and study the human body and its corporeal capacities (including its capacity to be controlled). New touch technologies, advancements in hearing aids, and the use of drugs, are examples of the ongoing transformation of bodily engagements. More recently, disciplinary boundaries have been broached, and the social sciences has turned to the study of "biosocial[1] becomings" and "organic thought" in order to better understand how the social and the biological operate across scales, beneath and beyond the human (Ingold & Palsson, 2013; Papoulias & Callard 2010; Wilson, 2015).

Alongside these changes, research into behaviour is now using new digital technologies that allow researchers to track bodily movement and activity beneath the time-scale of the human. Using micro-sensory technology, such as eye-tracking or EEG, we are learning to study the forces that contract to make a body. It turns out that the body is too big a unit of study! One can even dive deeper, tracking traits and flows of affect (and capital) across the micro-material aspects of relationality. To the extent that these new biotechnologies seem to plug into the body below the timescale of human perception, research has focused on how attention and engagement is powerfully sourced at the pre-individual (Abrahamson et al. 2016). Moreover, with new developments in brain imaging in the last two decades, there has been a radical increase in neurocognitive approaches to the study of mathematics, and number sense in particular (de Smedt & Grabner 2016; Nieder & Dehaene 2009). This research is important for how it centres a kind of knowing-in-the-body (Bugden & Ansari 2015; Dehaene 2011), but research on brain activity also feeds reductionist claims about neurobiology as the basis of learning. We have critiqued this research for that reason, and shown how important it is that mathematicians and mathematics educators pay attention to work in neuro-numeracy (de Freitas & Sinclair, 2016). Through neurocognitive research, and related policy, the mathematics student's body is being reconfigured and reassembled. Precisely for this reason, we believe that more research on mathematics education *as a matter of the body* is crucial today, as education policy becomes increasingly biomaterial in its governance. It would be foolish to simply dismiss or ignore the physiological, as one among many different kinds of bodily activity (Sheets-Johnstone 2012).

The turn to the body in mathematics education research incorporates many of these influences, and is a burgeoning area where diverse theoretical debates are occurring. Some of the various competing approaches have been outlined in de Freitas and Sinclair (2014) and in de Freitas (2016c). While some of the body theories are concerned with showing how behaviour *conforms* to current socio-material forces or neurocognitive constructs, non-dualist approaches such as inclusive materialism aim to rethink the matter-meaning mixture and the nature of learning (de Freitas & Sinclair, 2014). Inclusive materialism is interested in how the new emerges, how creative and material acts bring forth strange new ways of making mathematical non/sense. This entails a philosophical approach to mathematics that relies on key contributions from scholars such as Gilles Deleuze, Gilles Châtelet, Fernando Zalamea, Giuseppe Longo, Brian Rotman and Alfred North Whitehead.[2] Such an approach to body studies aims to better address the potential multiplicity of bodying processes, whereby bodies are made and remade, with porous boundaries, assembling with other bodies in ecologies of practice.

Bodies are 'situated', and are themselves actively involved in the making of socio-material milieus, and yet at the same time the body actively co-produces and contests these expressions

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[1] The term 'biosocial becoming' is taken from the anthropologist Tim Ingold who attempts to capture an integrated approach to thinking the biological and the social, the organism and the context, phylogeny and ontogeny, being and becoming—thereby challenging the reductionisms of both sociobiology and cultural constructionism.
[2] We are woefully aware of how this list is white and male. We are working to change that through the development of a new materialist philosophy of mathematics.

of difference through micro-gestures, somatic and other physiological habits. There are not only the different scales evoked by Lemke—the classroom, the group, the individual—but also other scales of mattering – the gesture, the brain, the economic system – which have generated enormous insights in the past few decades, but have remained rather isolated one from the other. Discussions of socio-cultural or political aspects of mathematics education often focus on the ways that institutional and discursive norms shape students' and teachers' experiences, but often fail to stray from the level of institution or social norm. While discussions of gesture and the role of sensory engagement rarely speak to how these practices fan out across classrooms, larger groups and environments. It is obvious to most educators, however, that the scales are not independent, and that they are at play in any actual teaching and learning event.

The challenge is then to find ways to link these scales without overcoding the one with the other. Reductive models of behaviour that insist our complex cultures are merely expressions of our genetic makeup or neurological arrangement may be compelling in their apparent explanatory power, but these have proven time and again totally unable to predict the vagaries of life. And yet equally inadequate are grand-sounding claims that 'everything is determined by economic and socio-cultural norms'. Both approaches overstate their case, and both perform the nasty theoretical habit of reducing multiplicity and diversity through overcoding, that is, by reading everything through their conceptual apparatus, without acknowledging the historical contingency of such apparatus. Not only is this problematic for its claim to explain everything, but in so doing it can only offer a rather empty gloss of that which is under study, and cannot encounter the new.

In this survey article, we wish to emphasize the need to develop research methodologies that are adequate to the complex socio-material practices comprising mathematical activity at different scales of mattering. In other words, we are focused on the challenge of how to integrate the socio-cultural and embodied work in our field, a challenge that seems to demand new theoretical approaches and research methods that are up to the task of making sense of mathematical bodies as they transversally stretch across different scales, be they micro-scales of nano-gestures or macro-scales of racialized bodies and language use. This is a tall order, and we put it forward as a provocation.

The methodological challenges of studying different scales of bodily mathematical activity—brain, gut, gesture, eye, gender, race, geolocation—is felt across different research approaches. In their commentary on a 2016 ZDM special issue on cognitive neuroscience and mathematics learning, Ansari and Lyons (2016) explicitly state the need to "move beyond the use of traditional paradigms that are derived from experimental psychology towards more ecologically valid research paradigms" (p. 382). This aim to study complex systems or ecologies also reveals the limits of conventional qualitative methods. As de Freitas et al. (2017) write:

> Many of the conventional qualitative research methods in education […] seem to recenter human agency in humanist terms, and ill equip researchers to study the complex nature of distributed agencies across social-material networks. Interviews, focus groups, and even standard protocol around classroom observation, all tacitly employ particular epistemic and ontological assumptions about what constitutes a body, an action, an event, and so forth. These practices emerged within the discursive psychology paradigms that dominated educational research in the 20th century. (p. 174)
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This raises the question of how different scales of mattering can be thread together for better understanding the relationship between mathematics and the body. How can we open up the conversation so that those working in embodied cognition and those working on the socio-political framing of mathematics identity might begin to work together? Should these approaches be combined additively, so that they complement each other in analyses of classroom activity? Or are they more intertwined, in such a way that questions about one will change the nature of questions about the other? Lemke's (2000) research into heterochrony, raises related questions, when he asks, "How do actions or events on one timescale come to add up to more than just a series of isolated happenings? […] How does a *community* emerge from many people-in-action? On how many different timescales is our social life organized? How does persistent organization on longer timescales constrain the likelihood of events on shorter timescales?" (p. 273). In a classroom environment, we can study individual students, or the classroom as a whole, or even other units (different-sized groups), each on their own timescales. How is the classroom subject to still larger-scale 'historical' and even geological processes, while also modulated and inflected by shorter timescale processes?

Lemke's approach shares some points in common with the proposal made by Mikulan and Sinclair (2019), which addresses the methodological challenge of doing research at multiple scales directly, and thus plays an important role in framing the special issue. The authors focus specifically on the question of how to study events at different scales. They argue against the pervasive tendency to collapse these different scales into a single, more or less coherent "story" about what happened, and instead put forward a method called *stratigraphy*, in which the different scales are to be read in superposition, that is, simultaneously, without collapsing them together. Thus the aim is to sustain some heterogeneity in the account, and to keep the dissonance apparent. Stratigraphy is different from Lemke's focus on the actualized and chronological continuity and sustenance of individual people, community or things, because of its concern with the virtual—that is, with the multiplicity of the real, which includes not just the actual but also the potential, that which could have happened at any moment.

The various articles in this special issue of ZDM begin to branch out across different scales of mattering; they link, for instance, insights about hand gestures to the enactment of power in classrooms. We frame this overall endeavour as an attempt to look for possible theoretical confluences and affiliations, building a rich patchwork of body studies in mathematics education research. These different approaches need to be in conversation with each other, to think across research contexts, problems and communities, so that new forms of inquiry and new questions can emerge. Here we have chosen to organise our writing around several themes for the purposes of mapping the research on which we focus. These themes can be seen as different approaches to configuring bodies. They have emerged from considering recent developments across the field, and are used here to help carve out areas for future research. They are: (1) groups, systems, ecologies (2) affect, movement, sensation, (3) language-use and gesture, (4) dis/ability and power, (5) technology, technicity, and tools.

2. Groups, systems, ecologies

Researchers drawing on activity theory (Engeström 1987; Lemke 2000; Leont'ev 1978; Vygotsky 1978) tend to focus on group interaction. They do so by conceptualising classroom interactions as complex systems in which any individual participation occurs in relation to the other people and material objects. Studies using this approach attend to language, bodily orientation and material interactions, and have thus become increasingly used in mathematics education research over the last two decades (Roth & Lee 2007). In a related fashion, Abrahamson, Flood, Miele, and Siu (2019) draws on enactivism, which is a theory that emerged from the biological sciences, to propose a framework for universal software design in mathematics education. They combine enactivism with ethnomethodological conversation analysis in order to pursue this socio-political interest in improving accessibility and usability of mathematics software.

Four other papers—by de Freitas, Ferrara and Ferrari (2019); Vogelstein, Brady and Hall (2019); Chronaki (2019); Alibali, Boncoddo and Pier (2019)—can also be seen as attempts to look at group behaviour, in their emphasis on the ensemble, ecological, and contagious nature of bodily movement and expression in mathematics learning events. For instance, de Freitas, Ferrara and Ferrari draw on observational methods to study the coordination of group movement, and corresponding circulation of sympathy, in a classroom that involves the use of a novel digital technology which enables learners to express mathematical relations by moving their arms. They emphasize the significance of the mathematical-material task in demanding that differently abled bodies be assembled together to engage with the fundamental indeterminacy of mathematical concepts. In other words, the 'group' endeavour remixes the concept-matter mixture, thereby entering into a learning-making process that engenders a new mathematical concept-object. Moreover, they aim to show how group learning is achieved through affect often without the deliberative 'cognitive' engagement of individual students. This occurs precisely because the pre-individual affect fuels trans-individual achievement often without the individual reflecting or internalizing the process.

Vogelstein, Brady and Halls' study is rooted in theories of embodiment, but aims to shift focus from individual body movement to group enactments (of mathematical dances) in order to study the distributed nature of learning and the intercorporeal establishment of social groups. In "foraging" for examples of complex material-mathematical activity in cultural practices, Vogelstein, Brady and Hall perform a kind of ethnomathematics diffracted through embodied cognition analysis. From a video of a large-scale coordinated event with hundreds of dancing bodies, they select a unit of activity (a group of four performing a series of movements), and practice it themselves, along with their research participants, in an attempt to uncover the mathematical relationships therein. Their study thereby makes methodological interventions in experimental design research, by focusing on the small group mathematical practices that are folded into large-scale public cultural events, bringing the micro-ethnographic to bear on the large-scale public performances of national identity. Their methodological innovation, that of reenactments, has some commonalities with the performances described in Chronaki (2019), in terms of the focus on thinking-in-movement, and insofar as the video analyses focus on "the people-plus-prop system", which recognizes the power of non-human material objects in learning processes.

Chronaki (2019) focuses on issues of equity in the mathematics classroom and in teacher education, and marshals the ideas of Foucault, Bahktin, and Walkerdine to make sense of micro-ethnographic observational data of group coordinated movements. Her methodological approach involves both a case study and a choreographic intervention, the latter allowing her to study the bodying of the participants, that is, how they become mathematical bodies through movement. Alibali, Boncoddo and Pier (2019) stems from their work in gesture studies, and is thus rooted in theories of multimodality, but also attempts to study the emergence of "common ground" in a mathematics classroom, thus shifting from the individual to the group scale.

3. Affect, emotion, sensation

There is a long tradition of research on the role of affect in mathematics education, dating to the 1980s. This early research drew heavily on psychological theories and focused on beliefs, attitudes and emotions (see McLeod 1992; Zan et al. 2006). More recent sociocultural perspectives have conceptualized affect (as beliefs, attitudes and emotions) in terms of socially organised phenomena that are constituted in discourse and shaped by relations of power (e.g. Evans et al. 2006; Sinclair & Heyd-Metzuyanim, 2014; Op't Eynde & Hannula 2006; Radford 2014). Both early and current researchers working in this domain tend to assign particular beliefs, attitudes and emotions to individuals (students and teachers), so that traits such as curious, anxious, positively disposed, etc., are seen as traits that often need to be encultured, changed or avoided in mathematics (e.g. Yackel & Cobb 1996; Goldin 2000).

As Hannula (2012) remarks, researchers have focused on individual emotional or motivational states, which means that there has been little attention to more collective or classroom-level research on affect (Hannula 2012). The work of enactivists such as Towers and Martin (Towers, Martin & Heater 2013; Martin & Towers 2015; Towers & Martin 2015) have sought to study mathematical understanding as a collective endeavour, but have not focused specifically on affect. However, Drodge and Reid (2000) use enactivism as a theory of embodied cognition to study the bodily basis of affect, and its relation to language and social contexts of "emotional orientation", which the authors see as a characteristic feature of mathematics. Theirs is a non-dualistic perspective that contrasts with the early research on emotions, while also attempting to grapple with the complex interaction of the body and the social in studying emotion. As de Freitas, Ferrara and Ferrari write in their article (this issue), there are several other theoretical approaches that can support the study of affect in a similarly entangled and distributed fashion, emerging in the humanities as part of "the affect turn".

There is also a growing interest in using insights from physiology to study the flow of affect in classrooms. For example, Youdell, Harwood and Lindley (2018) use a transdisciplinary approach that brings social and biological accounts together in order to study the distribution of "emotionality" in a classroom context—in which children are taking a mathematics test—through the study of the children's stress. They use mass spectrometry to capture and analyse exhaled breath, which includes compounds associated with physiological expressions of responses to stress. These authors described their work as attending to the scale of the more-than-social because it speaks to the physiology, neuroscience or biochemistry of stress.

Affect features strongly in the papers by de Freitas, Ferrara and Ferrari (2019), Chronaki (2019) and Lambert (2019), but also to a certain extent in the papers by Vogelstein, Brady and Hall (2019) and Alibali, Boncoddo and Pier (2019). de Freitas, Ferrara and Ferrari focus specifically on the concept of sympathy, or "feeling together", in collaborative mathematical tasks, which they frame as being both social and bodily. Rather than speak of emotions and their tendency to be seen as individualized inner states, the authors draw on contemporary work on affective ecologies where affect is treated as fundamentally relational and sourced at the infra-scale of the somatic body. They show how affect plugs the individual body into the trans-individual ecology, and fuels the making of mathematical concepts. Chronaki (2019) draws on some similar sources (Deleuze, Massumi, Manning) in her study of the body's capacity to affect and be affected—and, importantly, to affect in different ways than mandated by norms and assumptions, thereby taking the body as an agential, vital force that cannot be entirely determined by socio-political forces. In Lambert (2019), it is through the concept of complex embodiment that emotions are interpreted as being embodied, which enables her to study the affective and socio-political forces of disability and, in particular, to account for the negative experiences that are felt (and not just discursively reported or explained) by one young learner. The particular ways in which mathematics recruits this learner's body, by demanding attention, concentration and speed, all serve to tell a story that is much more complex than simply naming the emotional state.

In their focus on intercorporeality and the affective negotiation that it requires, Vogelstein, Brady and Hall are also working with affect in a distributed, relational way that resonates with the concept of sympathy. Similarly, the addressee gestures studied in Alibali, Boncoddo and Pier (2019), also seem to be concerned with the complex teacher-student interactions that often operate at sub-conscious levels and involve affectivity in terms of the bodily responses that arise between a teacher and a student, or a teacher and a classroom.

4. Language-use and gesture

Research on language-use and discourse has been extremely influential in mathematics education. This kind of work typically focuses on the discursive framing of experience, and underscores the power relations that are manifest in discourse. For instance, Staehler-Pohl and Gellert (2013) use Bernstein to code power relations in mathematics classroom discourse, and underscore the role of grammatical forms and particular use of pronouns and other linguistic devices. Similarly, semiotics has played an influential role in mapping mathematics meaning making, focusing as it does on the mediating role of signs—for example, in diagrams and other visual mediators—and studied for how the mathematics register encodes particular socio-economic positioning (e.g., O'Halloran, 2005). Despite the huge insights gleaned from this research, it tends to stay tuned to sign-making without always attending adequately to the differentiating potential of bodies in action. Decades of socio-cultural scholarship in this vein has produced important insights into the discursive shaping of mathematics student and teacher identity or subjectivity, but this work has often failed to examine the specific ways that mathematics is lived and produced through 'minor' material, embodied and often somatic practices. The word 'minor' is a theoretical term that Deleuze and Guattari (1987) use to describe the minor mathematics and minor sciences that are not always incorporated as part of a state curriculum, and we use the term here to reference the kinds of mathematical bodies that are not merely deficit or deviant, but are part of a mathematical practice in their own right (Gutiérrez 2017).

Rather than treat bodies as solely the product of discourse, many scholars across the humanities and social sciences are taking up the material dimensions of the body in a more expansive biopolitics (Coole & Frost 2010). Bohlmann (2019) adopts a sociological theoretical framework, drawing on insights from Bernstein (1996) like Staehler-Pohl and Gellert, to describe the qualitative nature of classroom interaction, but she couples her discursive analysis with a focus on the bodily movements of the teachers, thereby extending Bernstein's theory to include the embodied ways of framing school mathematics. Widening the observational methods, Bohlmann treats the various scales (micro-gestures and spoken language, in this case) as more or less complementing each other.

The focus on language-use in mathematics education research has begun to open up, due to a realization that other modalities must be studied alongside language-use. Radford (2014) weaves an analysis of discourse with attention to gesture, voice intonation, and traces the role of other media in this process. Roth (2011) has developed complex transcript coding practices for studying the rhythm, intonation and pitch of speech, in order to record such dimensions in the transcript. While Radford and Roth tend to focus on the particular timescale of the classroom event, Lemke (2000) extends his semiotic approach into multiple-timescales to study the formation and maintenance of school identity and community over very different timescales. His research focuses on the different longer-term processes and shorter-term events that are linked by material objects (including human bodies) which can function semiotically and materially to mediate the integration of social activities. At larger scales of analysis, new methods from the field of linguistics have been powerful in enabling researchers to study corpus data sets of discursive patterns, as in the work of Herbel-Eisenmann, Wagner and Cortes (2010) on the "lexical bundles" that indicate dominant discursive habits across a large corpus of data from classrooms. At the historical scale, Yolcu and Popkewitz (2019) perform a Foucauldian genealogical method, analyzing historical documents and policy texts, tracking the production of dis/ability in mathematics education. They show how the contours of the learner's body and its potential capacities are gradually configured through these historically situated texts.

Researchers interested in the role of gesture in mathematics teaching and learning share a concern for extending analyses of classroom interactions beyond linguistic channels. These include studies drawing on theories of embodied cognition (Lakoff & Núñez 2000), actor-network-theory (Latour 2005), multi-modal theories (Jewitt 2009; Goodwin 2017; Streeck, Goodwin & LeBaron 2011), and new materialisms (Barad, 2003; de Freitas & Sinclair 2013, 2014). This kind of work might involve examining the ways that children use their bodies to express mathematical concepts (Nemirovsky, Kelton & Rhodehamel 2013) or the interaction between the hands and eyes of a learner using a multitouch app (Sinclair & de Freitas 2014). These analyses have emerged alongside the increased pervasiveness of video cameras in education research. The role of video research in mathematics education may in part explain the growing interest in the body, given that video has displaced previous audio recordings as the dominant mode of recording observations. Video allows one to attend explicitly to bodily actions such as gestures, enabling researchers to go beyond attention to language in order to take into account the importance of space, place and the material.

5. Dis/ability and power

If the body is no longer seen as passive or bounded and autonomous, then body studies in mathematics education must attend seriously to the ways in which different bodies and different bodily configurations do and learn mathematics. The proposition that everybody can or should do mathematics masks the body's potential to differ and fails to recognize how mathematical concepts themselves are intertwined with both human and non-human materialities (Sinclair, 2019). As Healy and Fernandes (2011) show, the way in which mathematics is represented and communicated almost always tacitly privileges certain bodies over others.

Whilst research focused on disability in mathematics education was for a long time segregated to specialised psychology journals, body studies is bringing it to the forefront of the research field in new ways. Over the past five decades, there have been important changes in the way that dis/ability has been defined and identified. In the earliest approaches, which Borgioli (2008) describes as modernist, dis/ability was defined as a disorder within the individual. Then, in postmodernist approaches, disability was viewed as a social construction, and therefore often related to normative assumptions regarding difference. In either case, Borgioli argues that disability has been constructed using very narrow definitions of what counts as knowing and doing mathematics. Currently, many students labelled with a learning disability (LD) in mathematics are deemed incapable of conceptual thinking or problem solving and are offered highly directed step-by-step instruction and procedures (Baxter, Woodward, Voorhies & Wong, 2002; Fuchs, Fuchs, Hamlett & Appleton, 2002).

Modernist practices are evident in the way children labelled 'dyscalculic' are treated as having a disorder rather than being seen as part of a more complex environment in which number is thought and taught. Healy and Powell (2013) note that teaching number is usually done in an arithmetic-based way that is based on paper-and-pencil technology which values procedures over other more holistic or contextual strategies. Today, even though many children (up to 5%)

are diagnosed with dyscalculia, researchers such as Gifford (2006) have questioned its validity. While some neuroscientists are working on identifying the precise locations in the brain where dyscalculia is performed, there is no guarantee that any differences in those areas of the brain can explain students' mathematical behaviour, let alone lead to changes in instruction. Moreover, recent work in biology is showing how the peripheral nervous system (rather than the central nervous system) plays a much more powerful role than previously assumed (Wilson, 2015). New ways of thinking about the electric body are reshaping the life sciences, as computational biologists learn how the body performs (and mutates) without being directed by the central nervous system (Levin, 2018). These developments are yet to have their impact on research in education but they are important in that they further challenge the dualist assumptions that identify unitary causes for learning in the brain.

While prior approaches to disability all too often blamed students' failure in mathematics on their different learning competencies, recent work has drawn attention to the distinctive and inventive sensory habits by which such students gain access to the cultural capital of mathematics (Lewis & Lynn, 2018). We emphasize two important aspects of this work: (1) senses are malleable in that loss of one sense will impact and modify other senses, which may provide new avenues for learning; and (2) mathematics itself is imbricated with certain sensory systems and can change under different conditions. In relation to (1), Healy and Powell (2013) argue, drawing on the work of Vygotsky, that human organs like the ears and the eyes can be thought of as tools: children who cannot hear might use their eyes instead to learn number; children who cannot see might use their hands instead to learn shape. If sensation is distributed across an environment, we need to think about haptic-eyes and seeing-hands, and new ways of organizing the organs. And in relation to (2), de Freitas and Sinclair (2014) show how sensory fusions and altered rankings occur historically as well, examining how the body-who-sees-with-eyes becomes, over time, less or more privileged in the field of mathematics, as does the autistic body. In other words, the specificity of mathematics historically and geographically is itself entailed in our sensory make-up.

In *Teaching Mathematics to Deaf Children*, Nunes (2004) exemplifies both of these issues are at play in the case of deaf children. She shows how the seriality of speech (and hearing) can be challenging for deaf children to learn to count. While deaf children often underperform their hearing 'counterparts' on counting tasks, they actually perform better on tasks such as counting backwards and 'What number comes after this one?' Nunes ascribes this latter fact to the more spatial way of thinking that these deaf children develop and points out that such tasks are never used to establish norms around number sense. School mathematics curriculum is conceived around certain sensory assumptions.

Lambert (2019) and Abrahamson et al. (2019) most directly take up the issue of dis/ability, and both do so by addressing the biological and political in novel ways. Lambert's paper shows how theories of "situated cognition" emerging from the work of Lave (1988) and Lave and Wenger (1991) have contributed to the "social model" of disability research that focuses on how particular people with particular corporeal tendencies are produced as disabled. In these kinds of studies, the material body is often considered a passive medium by way of which social participation occurs, so that mathematics dis/ability is imposed on an otherwise indifferent body. Lambert pushes past these approaches, and uses theories of complex embodiment (Siebers 2008) to explore the emotional, embodied *and* political, relational dimensions of mathematics learning. Her narrative method, commonly used in disability studies, is rooted in discursive methods and attempts to study how mathematics learning *feels* for a disabled learner.

Yolcu and Popkewitz (2019) and Chronaki (2019) can also be considered relevant to our thinking about disability in mathematics education research. In Yolcu and Popkewitz's history of the construction of the able-bodied mathematics student, we witness how the very notion of ability is framed in policy texts to exclude both particular kinds of bodies and particular kinds of mathematics. For Chronaki, the bodies that are not able are seen to be the ones from different cultures, who speak a different language. Like many of the labels and codes that pervade mathematics education research—gender, sexual orientation, race—ability is itself deployed within a logic of negativity (Gutiérrez 2009). In his philosophy of difference, Deleuze (1994) argued that the only way to avoid the logic of negativity is by thinking "difference in itself", rather than difference as a comparison of two things (abled or disabled; male or female; black or white; straight or queer, etc.). In order to do this, we might need to re-think the body itself, to think of it at different scales that prevent us from collapsing it into the simple categories and binaries that are often used today. The proposal by Abrahamson et al. (2019) to think about universal design at the outset, rather than to adapt technologies designed for abled bodies, aims to disrupt this logic of negativity.

6. Technology, technicity, and tools

With increased focus on the body in mathematics education, researchers have drawn attention to how technologies alter the material medium and prosthetic nature of engagement. This has highlighted the fundamental technicity and materiality of mathematical activity, and the important role of tools. The theory of instrumental genesis has been used to study the way that artefacts become tools, highlighting the mutual transformation of the artefact and the student in a particular mathematical activity (Vérillon & Rabardel 1995). As the student uses the artefact to solve a particular problem, she develops certain actions and activities related to the artefact (utilization schemes) that in turn determine some functionality of affordance of the tool—for example, how to find the limit in $+\propto$ of a polynomial function using CAS technology (Trouche 2000). In this vein, the theory of semiotic mediation (Bartolini Bussi & Mariotti 2008) draws attention to the way in which artifacts can be transformed, with the help of the teacher, into mathematical signs through processes of modification and internalization (e.g., Bartolini Bussi & Baccaglini-Frank 2015). More recently, adaptations of activity theory that focus more specifically on the role of digital tool use have emphasized the complex, causal networks of relationships that comprise screen activity, thus providing an analytical lens that enables researchers to focus on the social dimensions of digital mathematical activity (e.g., Ladel & Kortenkamp 2016).

Aside from some notable exceptions (Papert 1980; Noss & Hoyles 1996), the research on the use of digital technology has been concerned with epistemological questions such as "how might this tool change or enhance the way that students acquire knowledge?" As we open up discussion about how bodies matter, we see a need to ask ontological questions about the very conditions for such epistemological insights. An ontological turn in mathematics education research seeks to show how technologies of all kinds have been involved in the historical evolution of entirely new kinds of mathematics (de Freitas, 2016a; Sinclair 2016). In Rotman's (2008) materially framed sense, mathematics has been engaged in a two-way co-evolutionary traffic with machines since its inception. If machines and mathematics are so imbricated, then the use of different machines will produce a different mathematics. It is according to this ontological perspective that some researchers are now choosing to study the changing nature of a physico-mathematics, rather than study how these tools mediate pre-determined mathematical meanings (de Freitas, Sinclair & Coles 2017). Research following Papert's vision has typically been concerned with changing the nature of learning but also, to a certain extent, with changing the mathematics itself—towards what Papert called a more "learnable mathematics". In this tradition, the research reported in Healy and Sinclair (2007), for example, uses dynamic geometry environments to shape both the nature of learning (through stories) and the nature of mathematics (through dynagraphs).

As de Freitas (2016b) argues, this shifts traditional teaching experiments into new territory where the digital tool might function as a diffractive apparatus, making visible the complex entanglement of concept and matter. Technology is thus imbricated with the associated milieu, so that analysis can focus on how students engage with the indeterminate and messy nature of physico-mathematical concepts such as force (de Freitas 2016b), symmetry (Chorney & Sinclair 2018) and number (Smythe et al. 2017). The methodological shift to studying concept-tool emergence follows recent developments in the humanities as scholars move towards a generalized environ/mentality in the study of digital life (Hörl 2017).This approach is also evident in de Freitas, Ferrara and Ferrari (2019), where the Wii graph digital tool is used to study the concept of functions as a sympathetic coordination of various movements both at the infra-scale (of affect), the human scale (of gesture), and the group scale (of shared achievement). Here it is not only the social dimension of activity that is highlighted, but also the affective one, with the digital tool playing an important role in making observable some of the pre-conscious, non-discursive aspects of mathematical activity that are often overlooked or underappreciated in cognitively driven theories used in mathematics education research.

Finally, digital technology is at the heart of Abrahamson et al. (2019), which proposes ‘universal’ design considerations when developing digital learning tools. The ideas of universal design are meant to be sensitive to the different ways in which different bodies engage with the material world, and are intended to reduce experiences of alienation and inequity. Abrahamson’s paper aims to offer guidelines for design interventions in mathematics education so as to not automatically divide students into able bodied and disabled, with particular focus on the body-biases built into curriculum around vision and sight. Exemplary work already occurring in this area, particularly with blind students, can be found in the research of Healy and Fernandes (2011) with inclusive classrooms in Brazil. Here digital tools are used by researchers to reshape the nature of mathematical activity, which usually privileges seeing and hearing students, and almost exclusively emphasizes visual and linguistic forms of mathematical representation. Across the field, we see new digital tools created to provide alternate, novel forms of interaction that do not rely on traditional representations, thereby providing different kinds of opportunities to dis-advantaged populations—such as numbers that can be apprehended through both colour and sound (Fernandes et al. 2011).

7. Conclusion

In this paper, we have discussed five key theoretical and methodological trends in the mathematics education literature that can enable cross-fertilisation across different researcher sites and interests: 1) groups, systems, ecologies (2) affect, movement, sensation, (3) language-use and gesture, (4) dis/ability and power, (5) technology, technicity, and tools. These all partake in different ways of in body studies but also vector towards long-standing and significant research areas in mathematics education such as group learning, emotions and beliefs, mathematical discourse, equity and technology-based teaching and learning. While not all these research areas have typically considered themselves as part of body studies, our survey shows that recent advances in the humanities and social sciences are making it clear that the body matters significantly in all questions about knowing, being, learning and valuing—especially when we adopt non-dualistic stances. We are eager to see new research questions and new methodological experiments that further nourish this cross-fertilisation.

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