



Multidimensional ecologies of mathematical life

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ABSTRACT

In this paper, I introduce multidimensional ecologies of mathematical life (MEMaL), a framework for understanding mathematics as a lived practice that extends across formal instruction and everyday life, and is shaped by social, material, and political conditions. MEMaL identifies five ecological dimensions. *Spatial ecologies* concern embodied engagement with tools, materials, and arrangements that organize participation. *Temporal ecologies* attend to the rhythms, repetitions, and durations through which mathematical ideas gain continuity. *Epistemic ecologies* concern locally valued criteria for credible or worthwhile mathematical knowledge, while *affective ecologies* foreground the atmospheres shaping recognition, belonging, confidence, and risk-taking. *Imaginative ecologies* address how individuals and communities envision mathematical futures, identities, and possibilities. MEMaL's distinctive contribution is its focus on ecological configuration: how spatial, temporal, epistemic, affective, and imaginative conditions come together and alter one another. Changes within one dimension can therefore reorganize possibilities for mathematical participation, recognition, and becoming across the wider ecology. These dimensions sit within broader political forces that shape an environmental context and determine whose participation becomes visible, credible, and valued. Mathematical activity, on this account, cannot be separated from environments that enable or restrain participation and shape whether that participation is recognized and valued. MEMaL therefore offers researchers and educators a way to examine these interdependencies and the mathematical lives they make possible.

Keywords: mathematical life, spatial ecologies, temporal ecologies, epistemic ecologies, affective ecologies, imaginative ecologies

INTRODUCTION

To understand how mathematical life takes shape across social and material environments, mathematics education requires perspectives that account for how mathematics is lived in classrooms, homes, public spaces, workplaces, community settings, and everyday routines. Research has illuminated many aspects of this life. Cognitive studies examine how pupils make sense of mathematical ideas and transform their understanding (Ben-Zeev & Star, 2001; Sfard, 1991); sociocultural research emphasizes participation in shared practices (Cobb et al., 2009; Nasir & Hand, 2008); identity scholarship shows how mathematical relationships are shaped by recognition, belonging, and positioning (Heyd-Metzuyanim & Sfard, 2012; Solomon, 2007); and research on affect demonstrates how emotions and self-perceptions shape participation (Grootenboer & Marshman, 2016; Hannula, 2019). These traditions offer substantial insight into particular dimensions of mathematical experience. Yet pupils encounter these conditions simultaneously. A learner's difficulty with a proof, for example, may arise from the interplay of conceptual demands, classroom norms, pacing pressures, emotional vulnerability, and family narratives about who is acknowledged as being "good at maths".

This analytic fragmentation is evident in how research questions are often framed and pursued. Curriculum research commonly examines policy, sequencing, and pacing, while giving less attention to learners' lived experiences of these arrangements (Choppin et al., 2014; Remillard & Heck, 2014). Affective research frequently approaches constructs such as enjoyment (Pinxten et al., 2014) and anxiety (Ma, 1999)

primarily at the individual level, offering more limited accounts of how emotions emerge through shared social and institutional environments. Sociopolitical scholarship has illuminated structural inequities in mathematics education (Gutiérrez, 2013; Pais & Valero, 2012), while also creating scope for closer examination of how such forces become consequential within moment-to-moment activity. Across these traditions, the field has developed considerable depth. A further challenge is to trace how multiple conditions converge, interact, and acquire meaning within lived mathematical experience.

A growing body of research provides resources for an integrative account. Studies beyond the classroom demonstrate how mathematical activity develops through practices in homes, communities, and extracurricular settings, locating mathematics across formal and everyday life (Civil, 2014; Turner et al., 2024). Research on embodiment and socio-materiality shows how mathematical thinking is organized through bodies, tools, gestures, and spaces (Arzarello et al., 2009; Shvarts et al., 2021; Sinclair & Ferrara, 2023). Scholarship on multilingual learning demonstrates how linguistic repertoires function as resources, with their value shaped by cultural and institutional recognition (Garza, 2017; Moschkovich, 2007; Sharma & Sharma, 2023). Identity-focused research further illustrates how these conditions shape participation and how people come to recognize themselves and be recognized by others as mathematical (Boaler & Greeno, 2000; Heyd-Metzuyanim & Sfard, 2012). Taken together, this work positions mathematics as inseparable from the relations and conditions through which it is enacted.

An ecological perspective offers a way to make these conditions integral to the substance of mathematical activity. Ecological approaches understand learning as emerging through relations among people, tools, discourses, norms, histories, and environments (Bronfenbrenner, 1976; Ingold, 2012; Renn & Smith, 2023). In mathematics education, this perspective shifts attention to the worlds that make mathematical participation possible. It directs analysis to how opportunities for participation, recognition, risk-taking, questioning, and belonging are organized through arrangements of space and time, expectations about knowledge, emotional atmospheres, and broader political conditions. From this perspective, these features constitute mathematical life.

In this conceptual paper, I introduce multidimensional ecologies of mathematical life (MEMaL), a relational framework for examining how mathematical life is produced through interconnected conditions. I use the term *ecological* to describe mathematical activity as emerging from ongoing relations among people, bodies, tools, spaces, temporal rhythms, forms of knowledge, emotional atmospheres, and imagined possibilities. MEMaL identifies five ecological dimensions: spatial, temporal, epistemic, affective, and imaginative. These dimensions are organized historically, politically, and economically, and their significance emerges from their relations with one another. Rather than treating any single dimension as the primary unit of analysis, MEMaL takes their configuration as its central analytic object.

I use the term *ecological configuration* to describe how spatial, temporal, epistemic, affective, and imaginative conditions become consequential together within a particular setting, episode, or trajectory of mathematical life. A configuration is dynamic: relations among dimensions can shift, intensify, or reorganize over time. Pacing, for example, can reshape affective risk and opportunities for reflection; material arrangements can redistribute epistemic authority; experiences of recognition can alter the forms of mathematical participation a learner considers possible; and institutional priorities can reorganize several dimensions simultaneously. I refer to such changes in their relational organization as ecological reconfiguration. MEMaL therefore provides an analytic language for examining how ecological relations produce, sustain, constrain, and transform forms of mathematical participation.

Relations within an ecological configuration can take different forms. One condition may enable another by opening up new possibilities or constrain it by limiting what can happen. Conditions may also amplify one another, compensate for constraints elsewhere, stabilize an existing pattern of participation, or come into conflict by creating competing demands or possibilities. I use these terms as heuristic rather than fixed categories whose meaning depends on the particular mathematical activity and setting being examined. What matters, then, is not simply that several ecological dimensions are present at the same time. Ecological reconfiguration occurs when the relations among those conditions change. A shift in one dimension may alter how others operate, producing a discernible change in mathematical participation, recognition, credibility, affective experience, or conceivability. Furthermore, political and economic forces are integral to these

configurations. Accountability policies, assessment regimes, institutional priorities, and cultural narratives about who is “good at maths” ultimately organize pacing, recognition, participation, risk-taking, and the value accorded to different forms of knowledge (Heywood & Chin, 2023; Schmitt, 1996; Warren, 1999). Politics thus operates through the dimensions themselves, shaping how mathematical environments are organized and which forms of participation become visible, credible, and valued.

MEMaL builds on established theoretical traditions while establishing a distinct analytic focus. Bronfenbrenner’s (1976) ecological perspective foregrounds relations between learners and their environments, while socio-material scholarship examines bodies, materials, affect, and institutional forces as intertwined within mathematical activity (Sinclair & de Freitas, 2019). Funds-of-knowledge research recognizes households and communities as sites of mathematical knowledge and examines how such knowledge travels and gains recognition across home and school contexts (González et al., 2001). Vygotskian perspectives emphasize socially mediated meaning-making through communication and participation (Steele, 2001), while realistic mathematics education foregrounds meaningful contexts, mathematization, interaction, and guided reinvention (Van den Heuvel-Panhuizen & Drijvers, 2020). MEMaL complements these perspectives by making the relational configuration of spatial, temporal, epistemic, affective, and imaginative conditions its primary analytic concern. Its distinctive contribution lies in examining how these conditions organize one another within historically and politically produced environments, and how their configurations shape which forms of mathematical participation become possible, recognizable, and valued.

CONCEPTUAL DEVELOPMENT AND GENERATIVE ORIENTATION OF MEMaL

The conceptual architecture of MEMaL brings into relation scholarship on embodiment and materiality, temporality, epistemic practice, affect, imagination, and sociopolitical organization, treating these as mutually conditioning dimensions of mathematical life. The five dimensions serve as analytic distinctions for tracing configurations of mathematical life across settings. Their explanatory salience varies with the phenomenon and evidence under study, and particular dimensions may become more consequential in specific configurations. A MEMaL analysis therefore extends beyond assigning observations to discrete categories. It examines how conditions acquire significance through their relations and how those relations organize possibilities for mathematical participation.

Underlying this analytic approach is a generative conception of theory (Gergen, 1978), in which theoretical resources enable phenomena to be seen differently, questions to be reframed, and explanatory possibilities to be expanded (Smith-Lovin, 2000). Theoretical work in mathematics education has similarly emphasized the productive interaction of heterogeneous perspectives (Kirshner et al., 2010; Prediger, 2019; Radford, 2008). Within MEMaL, this generative orientation concerns primarily the framework’s analytic capacity to disclose relations among conditions that might otherwise be examined separately and, in doing so, to open new questions about how mathematical life is organized. The five dimensions thus function as relational resources for tracing how ecological conditions interact, reinforce, constrain, and reconfigure one another across settings.

MEMaL, Complexity, and Ecological Emergence

Where generativity describes what MEMaL enables analytically, ecological emergence concerns what takes shape through relations within mathematical life. This focus on how relational configurations generate possibilities for participation, recognition, and brings MEMaL into productive dialogue with complexity theory. Davis and Simmt (2003), for example, conceptualize mathematics classrooms as adaptive, self-organising systems in which collective possibilities emerge through interactions among participants and may exceed any participant’s independent contribution. Their relational account resonates with MEMaL and also helps clarify its distinctive concern with the multidimensional configuration of the conditions through which emergence takes particular forms.

The two perspectives, nevertheless, differ in their explanatory emphasis. Complexity theory foregrounds emergence and self-organization, attending to how interactions among agents, together with conditions such as diversity, enforcing restraints, decentralized control, and patterns of interaction, give rise to forms of individual and collective learning that cannot be reduced to the actions of particular individuals (Beswick et

Table 1. MEMaL in relation to neighboring theoretical perspectives

Perspective	Central analytic object	Primary explanatory emphasis	Additional analytic contribution offered by MEMaL
Bronfenbrenner's (1976) ecological perspective	Relations between individuals and environmental systems	How development and experience are shaped through relations across environmental contexts	Specifies spatial, temporal, epistemic, affective, and imaginative conditions within mathematical life and treats their relational configuration as an analytic object
Socio-material approaches	Relations among bodies, materials, practices, affect, and institutional forces	How activity is constituted through entanglements of human and material relations	Provides differentiated ecological dimensions for tracing how material, temporal, epistemic, affective, and imaginative conditions organize one another within mathematical activity
Funds-of-knowledge research	Knowledge developed in households and communities and its relation to schooling	How historically and culturally developed knowledge is mobilized and recognized across home and school contexts	Examines how the recognition and use of such knowledge are shaped by wider configurations of spatial, temporal, epistemic, affective, and imaginative conditions
Vygotskian perspectives	Socially mediated meaning-making and participation	How learning develops through communication, mediation, and participation with others	Extends attention to the ecological conditions through which particular forms of mediation and participation become possible, credible, sustainable, or constrained
Realistic mathematics education	Mathematization within meaningful contexts	Guided reinvention, interaction, modelling, and movement between contextual and formal mathematical activity	Examines how the surrounding ecological configuration shapes who can participate, which forms of reasoning are recognized, and which mathematical possibilities become available
Complexity theory	Adaptive and self-organising learning systems	How new possibilities emerge through interaction, diversity, enabling constraints, decentralized control, and self-organization	Focuses on the multidimensional ecological conditions through which emergent mathematical activity acquires particular forms of legitimacy, affective consequence, participation, and possibility

al., 2010; Deogratias, 2018). MEMaL, by contrast, focuses on how the environments in which such emergence occurs are ecologically configured. It traces the spatial, temporal, epistemic, affective, and imaginative relations through which mathematical activity becomes possible, credible, sustainable, risky, recognizable, or imaginable, while attending to the political and economic forces that organize these relations. Complexity theory therefore theorizes how learning systems emerge and develop, whereas MEMaL provides a vocabulary for analyzing the multidimensional conditions through which that emergence takes particular forms as mathematical life.

This distinction is especially important in relations between individual and collective learning. An idea may emerge through collective mathematical activity yet remain unevenly available, credible, or inhabitable across participants. Collective norms of explanation, for example, may stabilize an idea at classroom level while making participation precarious for pupils whose gestures, language practices, tempos, or forms of reasoning receive limited recognition. MEMaL makes this unevenness visible by examining how the same ecological configuration can sustain collective mathematical development while positioning participants differently within it. In this way, it complements complexity accounts of emergent mathematical communities by tracing how ideas become materially enacted, temporally sustained, epistemically authorized, affectively experienced, and imaginatively extended. Davis and Sumara (2005) caution against treating complexity science as a meta-theory that subsumes other perspectives. MEMaL adopts a similar configurational stance, examining relations among conditions that other theories may illuminate separately.

To make these distinctions more explicit, [Table 1](#) summarizes the different analytic objects and explanatory emphases of neighboring perspectives and identifies the additional analytic contribution offered by MEMaL. MEMaL complements these established explanations of learning, mediation, knowledge, materiality, and emergence by bringing their relational conditions into a shared analytic frame. Its distinctive analytic contribution is to make the relational configuration and reconfiguration of spatial, temporal, epistemic, affective, and imaginative conditions the central object of analysis.

Spatial Ecologies

To explore how mathematics becomes lived experience, we can begin by examining how space shapes what people can do, notice, and value. By spatial ecologies, I refer to the material, bodily, and social arrangements through which mathematical activity gains presence and meaning. These arrangements organize participation, visibility, and intellectual work. The placement of bodies and tools, the design of routines, and the expectations circulating through them guide who engages in mathematics, how contributions are recognized, and which ideas take form. Research across classrooms, workplaces, and digital environments shows that mathematical engagement develops through embodied interaction and tool use, as thinking unfolds in relation to the environments that sustain it (de Freitas & Sinclair, 2013; Flood et al., 2020; Triantafyllou & Potari, 2010).

One aspect of spatial ecologies concerns the arrangement of bodies and artefacts. In classrooms and workplaces, mathematical thinking forms through gestures, shared objects, and collaborative routines. Studies of embodiment show that gestures and sensory engagement with tools help create ideas rather than merely express existing thoughts (Flood et al., 2020; Radford, 2014). Workplace research further shows that specialized tools and inscriptions hold and communicate mathematical expertise (FitzSimons, 2013; Triantafyllou & Potari, 2010).

A second aspect concerns the organization of visibility. Mathematical participation gains value when social and material arrangements make it perceptible. In homes and community settings, everyday activities such as estimating or measuring become recognized as mathematical when someone explicitly names them as expertise (Aubrey et al., 2003; Quintos et al., 2024). In workplaces, mathematical thinking often becomes visible when standard procedures break down and people examine hidden computational structures (Williams & Wake, 2007). Digital environments also shape visibility, as interface settings influence whose contributions are acknowledged (Valasmo et al., 2023).

A third aspect involves the distribution of authority. Classroom layouts, grouping arrangements, and interaction formats influence who is recognized as a contributor (Lloyd, 2008). Beyond schooling, community partnerships show that reorganizing relationships between homes and schools can position parents as designers of mathematical learning alongside educators (Quintos et al., 2024). These roles draw on wider familial histories in which attitudes toward mathematics circulate across generations (Quaye & Pomeroy, 2022).

Spatial ecologies also involve the material production of concepts. New materialist and cultural historical research emphasizes that ideas emerge through engagement with artefacts, gestures, and inscriptions (de Freitas & Sinclair, 2013; Radford, 2014). In workplaces, diagrams, machines, and routines carry procedures, allowing reasoning to unfold through professional tasks (Triantafyllou & Potari, 2010). In classrooms, physical and digital tools allow learners to feel relationships, compare forms, and build distinctions through manipulation (Flood et al., 2020).

The politics of space shapes mathematical environments by establishing the conditions through which mathematical life takes form. Elden's (2007) analysis shows that space is continually produced through institutional and cultural priorities that organize its role in social life. Butler (2012), in turn, emphasizes that participation grows from systems of recognition that determine whose presence is acknowledged and made perceptible. Space can therefore be understood as a political conception that shapes action by distributing opportunities for participation differently across settings (Dikeç, 2012). These perspectives illuminate how spatial arrangements, pacing demands, grouping practices, and digital infrastructures organize whose reasoning becomes visible, who is validated as mathematically capable, and which forms of knowledge take hold. Political bias structures spatial ecologies by continually creating conditions that invite or restrict participation. Mathematical spaces, whether formal sites of instruction or informal places of exploration, encourage particular movements, expressions, and forms of risk taking, shaping participation before any task is introduced.

Recognizing these political forces clarifies that spatial arrangements do more than facilitate mathematical thinking. They regulate its possibilities. This becomes visible across varied educational and social environments, including homeschooling interactions, workplace training, prison learning programs, and mathematical projects led by communities. In these settings, distinct spatial and institutional priorities

generate different forms of autonomy, community, and practical engagement (Xenofontos, 2025c). In settings shaped by policy, pressures for efficiency and standardized outcomes narrow opportunities for inquiry and constrain the agency of facilitators and learners (Xenofontos, 2025b). Priorities such as care, surveillance, or accountability shape what mathematics is expected to accomplish and for whom it is imagined. Spatial ecologies therefore reveal how mathematical life unfolds through bodies, tools, and materials animated by institutional settings that configure their possibilities.

Temporal Ecologies

Temporal ecologies refer to the rhythms through which mathematical work develops. They concern how ideas, skills, and practices grow through sustained activity, repetition, gradual stabilization, and familiarity. From this perspective, mathematics takes shape through time. Gestures consolidate into ideas, procedures become reliable through recurring use, and practices such as measuring, cutting, estimating, or abstracting unfold through patterned routines. Mathematics emerges through the tempos of thinking and acting with language, symbols, and tools. This view echoes work in mathematics education and philosophy that treats mathematics not as a timeless object but as something that comes into being through time, as in de Freitas' (2013) account of mathematics as an event and Glasnović Gracin and Trupčević's (2022) argument that time is an educational resource shaping engagement with ideas. Temporal ecologies therefore suggest that each site of mathematical activity has distinctive rhythms governing how ideas emerge, stabilize, and persist.

These ecologies challenge familiar narratives of mathematics as timeless truth waiting to be discovered. Historical work shows instead that mathematical certainty develops gradually. Grabiner's (1974) study of 18th century calculus, for example, describes how notions of rigor emerged as mathematicians moved from rapid symbolic manipulations toward more deliberate analyses of limits and continuity. What we now regard as established mathematical objects gained credibility through long histories of justification rather than appearing fully formed. This view resonates with Eppe's (2011) description of mathematical objects as dependent on research cultures that change and eventually stabilize through practice. Even a completed proof, often treated as a moment of absolute clarity, rests on extended periods of failure, revision, and reinterpretation. Time does not simply surround mathematics. It helps bring it into being.

When attention shifts to these processes, mathematical ideas appear as outcomes of repetition, anticipation, and patience. Their formation varies across settings. A carpenter adjusting a diagonal cut, a researcher rewriting an argument, and a child repeating a gesture to approximate symmetry all refine precision through iterative adjustment (Millroy, 1991). These refinements may eventually feel instantaneous, although they arise from long histories of practice. Mathematics inherits the tempos of bodies, tools, and environments. Teachers frequently report that complex topics require sustained engagement, yet curricular pressures restrict time for open problem solving, geometry, or collaborative work, a tension noted by Glasnović Gracin and Trupčević (2022). Mathematics thus unfolds as an evolving event rather than a static body of knowledge. Some temporal rhythms appear directly in movement. Studies of gesture show that mathematical reasoning often emerges through motion rather than only through symbols or diagrams. Ng and Sinclair (2013), for example, describe how a rotation may first be understood through physical gesture and only later represented symbolically. Gesture does not merely illustrate thought but actively shapes approximation, prediction, and transformation, showing how mathematical thinking depends on temporal processes that cannot be reduced to clock time.

Philosophical accounts of time further illuminate this lived dimension. Kakkori (2013) distinguishes between calculative time, measured by schedules, procedures, deadlines, and ecstatic time, experienced through stretches, pauses, and returns. Mathematical activity moves through both. Classroom life is often governed by timed tasks and curricular pacing, while understanding unfolds through irregular durations. A rapid calculation may rely on years of habituated logic. A conjecture may take decades to prove, with some problems awaiting resolution for a century or more as knowledge, tools, and collective attention shift (Hisano & Sornette, 2013). A rule of thumb may become trustworthy within an afternoon. Mathematical tempos are therefore layered, uneven, and intuited. This unevenness also appears in how mathematicians come to believe proofs, since confidence can spread suddenly across a network of ideas, producing a rapid shift from uncertainty to conviction (Viteri & DeDeo, 2022).

Temporal relations are also shaped by material and political forces. Institutional pacing, workplace demands, and production cycles generate distinct rhythms of revision and inquiry. Osborne (1994) describes such temporal regimes as shaping what kinds of futures feel possible, and this applies equally to mathematics. Some ideas are given time to grow, others are hurried toward closure, and some remain suspended. Recent work in mathematics education highlights the importance of recognizing temporal diversity. Appelbaum (2023), for instance, explores nonlinear queer temporalities in mathematical learning, where progress loops, pauses, and resists orderly sequences. Xenofontos and Appelbaum (2025) similarly argue for recognizing recursive and unpredictable rhythms in mathematical activity. Together, these perspectives deepen a view of mathematical time as varied, contingent, and lived.

Epistemic Ecologies

Epistemic ecologies describe how mathematical meaning develops within the lived environments where reasoning takes place. They shape how individuals and communities interpret ideas, recognize credibility, and experience conviction. Mathematics appears less like a stable body of knowledge than as a set of situated sensibilities that organize what counts as a compelling or sufficient explanation. These sensibilities grow through habits of attention, shared evaluative criteria, and expectations of elegance, coherence, or precision. Mathematical reasoning is therefore not only about reaching correct answers, but also about learning which questions matter, what feels satisfying, and what deserves attention in solving a problem. Mathematics functions as a way of seeing that takes form within particular cultural and historical trajectories (Hersh, 1997). Research in critical mathematics education highlights the interplay of community knowledge, formal techniques, and socially situated critique in this development (Gutstein, 2016). This perspective aligns with studies showing how mathematical activity is interwoven with cultural practice rather than isolated from it (Hunter, 2022; Razfar, 2012). Such ecologies emerge through shared understandings of what is mathematically credible, formed not only in schools but across domestic, occupational, and informal settings.

Different environments cultivate distinct ways of sensing when knowledge holds. Some foreground conciseness and symbolic organization, while others value iterative refinement, cumulative insight, or reliable procedural outcomes. A calculation may be valued for capturing a pattern succinctly, meeting situated demands, or reflecting commitments such as fairness, efficiency, or artisanship. In early childhood cooking activities, for example, mathematical reasoning gains force through measurement, tool sharing, and proportional decisions (Jo & Son, 2022). In immigrant communities, mathematics may serve as a symbolic and practical path toward security, fostering dispositions that emphasize diligence and correctness (Khilji & Xenofontos, 2024). Such cases show how mathematical conviction grows through situated tastes and what communities find persuasive.

These situated judgements also produce aesthetic expectations regarding explanation (Dreyfus & Eisenberg, 1986). A proof may persuade through conceptual clarity or economy, while a practical strategy may be judged through resourcefulness, frugality, or responsiveness to constraint. Explanations become compelling when they resonate with the epistemic atmosphere receiving them. Gesture, bilingual exchange, and improvisation may support substantial conceptual reasoning even when they fall outside formally recognized categories of explanation (Razfar, 2012). Teachers' assumptions about what constitutes mathematics therefore influence which forms of reasoning are acknowledged and which remain obscured (Xenofontos, 2018). As Harel (2008) observes, mathematical understanding includes both results and the ways of thinking that generate them.

Attention to what counts as credible also cultivates distinctive sensitivities to variation, analogy, and generality. Some settings privilege abstraction and unification across examples, while others attend to contextual distinctions with social or material consequences. Practices such as partitioning food, organising beadwork, or predicting local games foster generalization through repeated experience (Jo & Son, 2022; Razfar, 2012). In these cases, generality supports practical coordination as much as conceptual elegance. Such sensibilities arise through local histories of practice and become significant resources for mathematical learning (Andrews et al., 2005; Garcia-Olp et al., 2022).

Institutional and political conditions further direct epistemic partiality. Accountability regimes often favor streamlined reasoning and definitive outcomes, whereas community based educational spaces may emphasize relational knowledge, accumulated insight, and iterative refinement. Economic conditions may

cultivate values of efficiency or durability. School traditions have historically privileged Eurocentric modes of symbolic manipulation, positioning particular forms of judgement as normative (Hunter, 2022). These priorities distinguish community knowledge from formal knowledge and shape what institutions value as mathematics (Gutstein, 2016). Ethnomathematics research shows how mathematical forms emerge through culturally situated needs, extending conceptions of mathematical legitimacy (d'Ambrosio, 1985). Mathematics grows through what communities collectively pursue and consider worthy of intellectual attention.

Taken together, these processes invite an account of mathematical knowledge as a cultivated disposition. Such dispositions guide how individuals trace coherence, engage with uncertainty, and experience completeness in reasoning. They develop through identities as mathematics learners and through communal narratives about who may participate in mathematical activity (Hafeez & Xenofontos, 2024; Khilji & Xenofontos, 2024). Mathematics gains presence through particular tastes for reasoning, shaped by atmospheres in which certain ways of knowing appear compelling. Learning mathematics entails entering these fields of shared sensibility, where reasoning develops alongside perception, appreciation, and the intellectual pleasures of insight.

Affective Ecologies

Affective ecologies concern how emotional, relational, and embodied forces circulate within mathematical environments, shaping how mathematical life is inhabited across settings. These ecologies span schools, workplaces, homes, digital platforms, public institutions, and everyday interactions where people encounter and produce mathematical ideas. Affect emerges as a situated force created through arrangements of tools, pacing, expectations, authority, and recognition that make mathematical activity possible. Frustration, shame, curiosity, confidence, boredom, pride, and playfulness take shape through relations among bodies, spaces, materials, and histories that configure what mathematics becomes and how it feels. This view echoes critical affect studies, which distinguish affect from emotion and emphasize preconscious relational intensities that organize human action within political and social fields (Crociani-Windland & Hoggett, 2012).

Within different sites of mathematical life, emotions arise through affective atmospheres, the shared intensities moving through interaction, rather than through subject matter alone. Affective ecologies therefore direct attention to how spaces, routines, and relations organize anxiety, confidence, and curiosity. In workplaces, everyday mathematical errors become emotionally charged when made public, inviting threat, embarrassment, or self-protection in cultures where error signals incompetence or risk (Rausch et al., 2017). Learning flourishes in atmospheres that allow errors to be examined with dignity and through collaborative inquiry. Across university mathematics programs, pupils describe crisis when institutional structures accelerate pace, heighten comparison, and emphasize depersonalized knowledge, creating frustration, alienation, and self-doubt (Di Martino et al., 2023). In these circumstances, affect belongs to institutional systems rather than individual dispositions.

Affective ecologies also develop through recognition and belonging as relational conditions that grant legitimacy. Mathematics becomes inhabitable when authority figures, peers, and institutional rituals affirm participation. Teacher emotional support, for instance, fosters motivation, help seeking, persistence, and engagement with challenge (Skaalvik et al., 2015). In early education and family contexts, affective orientations toward mathematics circulate through everyday practice, forming generational inheritances that align certain identities more closely with the subject (Jenßen, 2022; Reyes, 1984). Gendered and socioeconomic patterns of confidence and anxiety arise through repeated encounters with praise, surveillance, and visibility (Hafeez & Xenofontos, 2024). Across community and diaspora settings, mathematics can become a source of safety, aspiration, or dignity, cultivating attachments that shape how it is valued (Andrews et al., 2005; Khilji & Xenofontos, 2024).

One mechanism within affective ecologies is the architecture of visibility. This concerns who displays reasoning publicly, whose contributions are scrutinized, and whose mistakes remain private and protected. Public classroom performance can generate silence, shame, or withdrawal among pupils whose participation is exposed, whereas smaller collectives redistribute risk and generate shared confidence (Hafeez & Xenofontos, 2024; Khilji & Xenofontos, 2024). Digital settings can reverse these dynamics. During pandemic distance learning, pupils usually associated with high achievement experienced more negative emotions when opportunities for public affirmation diminished, whereas pupils with low grades encountered less

anxiety and greater access to mathematical activity as their efforts became less exposed (Sydänmaanlakka et al., 2024). The emotional terrain of mathematics therefore shifts with spatial, technological, and institutional design. Affect is designed, arranged, and cultivated.

Understanding affective ecologies also requires attention to affective intensities, including pervasive unease, anticipation, resentment, or excitement that circulate before becoming identifiable feelings. This distinction in critical affect studies (Crociani-Windland & Hoggett, 2012) resonates with Zembylas' (2006) concept of witnessing, in which classrooms engage discomfort as ethical work. Similar intensities shape mathematical sites. Timed assessments produce urgency, competitive pride develops around speed, and moralized shame grows around "not getting it". These forces act as atmospheric pressures that determine which mathematical lives seem imaginable. Recognizing them reveals mathematical settings as moral and political terrains. From this perspective, I have drawn elsewhere on allegorical scenes in Dante's *Inferno* to illustrate how mathematical exclusion can take the form of displacement, mechanization, and silence. These operate as environmental conditions shaping participation rather than as individual deficiencies (Xenofontos, 2025a).

Affective ecologies ultimately present mathematics as a practice that organizes feeling through its material, temporal, epistemic, and political arrangements. Across schools, workplaces, families, communities, and digital platforms, mathematical settings cultivate what can be sensed, desired, valued, or resisted. Emotional life becomes a constitutive condition of participation, shaping who appears as a legitimate holder of knowledge, how knowledge comes to matter, and which futures feel attainable. An ecological perspective invites research and practice to approach affect as a collective design concern, where fostering curiosity, dignity, and belonging is inseparable from cultivating mathematical ideas.

Imaginative Ecologies

I call the final type imaginative ecologies, referring to how mathematical possibilities are sensed, projected, and lived in everyday life and institutions. These ecologies show how people imagine what mathematics could become, who belongs in mathematical worlds, and which futures seem attainable. Imagination appears as a socially cultivated capacity shaped through relations among bodies, tools, histories, and political conditions. In mathematical practice, it emerges through acts such as conjecturing and visualizing, where reasoning depends on constructing and manipulating diagrams, symbolic inscriptions, and hypothetical objects (Campos, 2010). It is also shaped by debates about whether mathematical ideas are discovered or invented, which position imagination as either revealing existing truths or producing new mathematical entities (Arana, 2016; Wenzel, 2013). These differing ontologies contribute to wider cultural narratives about mathematical ability and creativity, influencing who is recognized as participating legitimately in the creative labor of mathematics (Degu, 2020).

Mathematical imagination develops through interaction with material and symbolic resources. Research shows that people picture hypothetical objects and transformations through gesture, bodily movement, diagrams, notation, and tools (Nemirovsky & Ferrara, 2009; Wibowo et al., 2017). Imagination prepares the ground for action by giving abstract concepts perceptible form and connecting ideas with materials (Nikulin, 2008). Scholarship linking mathematics, literature, and aesthetics shows how imaginative activity gives abstract structures sensory meaning, allowing mathematical entities to be visualized, narrated, and experienced as tangible (Mazur & Pesic, 2005; Saiber & Turner, 2009). Mathematical thinking therefore emerges through embodied movement and representational practices that bring concepts into perceptual and practical form.

These ecologies nurture possibilities grounded in logical rather than empirical necessity. Mathematical activity routinely involves constructing hypothetical situations and exploring their necessary consequences, whether or not they correspond to actual phenomena (Campos, 2010). Public reasoning in mass societies similarly depends on imagination, as policy attitudes and evaluations of distant others draw on mental simulations that become objects of social and political cognition (Petersen & Aarøe, 2013). Everyday projections of earnings, interest, or household needs also rely on structured mental modelling, using heuristic rules to imagine future states and guide decisions (Todd & Gigerenzer, 1999).

The mathematical futures that take form are shaped by political and cultural forces regulating how mathematics is understood and who is imagined as capable of participating. When mathematics is framed as rigid or procedural, imaginative engagement narrows and opportunities to conceive alternative meanings diminish (Degu, 2020). This restriction is not neutral. Imagination can be politically constrained because the power to define legitimate knowledge determines which futures are thinkable and desirable (Bottici, 2011; Latimer & Skeggs, 2011). Educational practices can reinforce this limitation when assessment systems prioritize accuracy and fixed responses over exploratory reasoning or divergent conjecture, implicitly discouraging creative mathematical thought (Degu, 2020). These effects are uneven. Access to recreative imagination and spatial visualization, both central to mathematical sense making, varies considerably and is reduced for learners with disabilities unless supported through intentionally inclusive pedagogies (Sabirova et al., 2020). Even helpful imagery can constrain reasoning when pupils rely on fixed prototypes rather than transform or reinterpret them. Familiar representations such as the standard triangle image can both support and limit mathematical thought (Presmeg, 1992).

Imaginative ecologies also develop through narrative. Historical and literary accounts can present number, measurement, and symbolism as contingent human inventions, inviting practitioners into unfamiliar conceptual worlds. Historical engagement can provide access to alternative logics and symbolic systems, including different bases and nonstandard notation (de Vittori, 2021). Beyond academic settings, narratives circulating through families, media, workplaces, and communities shape which forms of mathematical agency feel conceivable or legitimate. These narrative climates also condition anticipatory imagination, influencing how people project mathematical practices and worlds not yet lived (Chapman, 2008).

Imaginative ecologies intertwine with the spatial, temporal, epistemic, and affective conditions that sustain mathematical life. Environments shaped by pressure, speed, or narrow definitions of correctness can restrict what becomes mathematically imaginable (Boaler, 2016). By contrast, settings that welcome conjecture, bodily exploration, and narrative experimentation in workshops, kitchens, laboratories, or professional learning communities expand the situations in which mathematical futures can emerge. Drawing on the wider politics of imagination, these settings can be understood as political climates regulating who may imagine mathematically and which mathematical dreams acquire value (Bottici, 2011; Latimer & Skeggs, 2011). Imaginative ecologies therefore concern the conditions that enable people to encounter themselves as mathematical beings, inhabit alternative mathematical worlds, and use mathematics to envision new social and intellectual possibilities.

Tracing Mathematical Life Across Settings

After school, nine-year-old Lila assists her aunt in preparing pastries for a community gathering. She is asked to ensure that the pieces of dough are “about the same size”. Lila places the pieces side by side on the counter, flattening each with the palm of her hand and adjusting their edges through alignment rather than measurement. She repeatedly refers to the baking tray to assess how many pieces might fit, and when inconsistency appears, she does not alter the dough itself but rearranges the configuration of pieces to achieve visual uniformity and efficient spacing. Her aunt acknowledges her activity as evidence of a “good eye”. Yet in school mathematics lessons, Lila reports discomfort with fraction tasks and claims she “cannot make equal parts properly”.

Lila is a fictional character, designed to illustrate a recognizable form of mathematical life rather than to represent empirical data or a particular research participant. At the same time, she is intentionally believable: many of us have known someone who can relate to Lila, because the vignette draws on familiar educational experiences and on traditions of educational fiction, in which fictional scenarios are informed by researchers’ experience and used to illuminate social and educational phenomena (Hrastinski, 2023; Watson, 2011). This scene does not represent a contradiction between mathematical success at home and difficulty at school. Rather, it illustrates how mathematical life is shaped by the ecological conditions that render some forms of reasoning fathomable as mathematics and others invisible. In Lila’s home environment:

- Spatially, mathematical reasoning is distributed across materials and bodies: dough, trays, hands, and alignment function as mathematical tools.

- Temporally, precision emerges through recursive adjustment, without an imposed pacing or evaluative interruption.
- Epistemically, adequacy is determined through contextually meaningful criteria – visual coherence, practicality, and arrangement – rather than symbolic accuracy.
- Affectively, recognition is relational and situated, producing confidence without the risk of scrutiny or comparative judgement.
- Imaginatively, Lila anticipates possible arrangements, modelling future configurations without formal representational systems.

When read together, these dimensions show how one condition enables and modifies another. The material arrangement of dough, trays, hands, and visual alignment supports recursive adjustment; the absence of imposed pacing allows that process to develop; and the aunt's recognition of a "good eye" establishes the activity as epistemically credible while reducing affective risk. This configuration enables Lila to anticipate possible arrangements and inhabit the activity as a competent mathematical participant. No single dimension explains the difference between Lila's two experiences; the difference is produced through their configuration.

In school, this configuration is reorganized, producing a shift in climate rather than an inadequacy of understanding. Only particular forms of thinking – measurable, symbolically verifiable, and rapidly executed – are recognized as legitimate in school environments. Home-based mathematical expertise becomes unintelligible in the classroom because it is not supported by the same spatial tools, temporal expectations, epistemic criteria, affective atmospheres or imaginative resources. In this sense, Lila's identity does not reflect mathematical ability alone; it is produced, strengthened, or jeopardized by the conditions of a given environment in which mathematical participation becomes recognizable and sanctioned.

To synthesize how these dimensions operate as environmental conditions rather than personal attributes, **Table 2** provides a comparative overview. Although the ecological dimensions are presented separately for analytic clarity, they do not operate independently. In practice, they interact, overlap, and sometimes conflict. A classroom may cultivate temporal space for slow inquiry, yet policy pressures for rapid pacing constrain how long uncertainty can be tolerated. An environment may strive for affective safety, yet the epistemic culture of mathematics often relies on critique, rigor, and public justification, which can feel exposing when trust is fragile. Similarly, imaginative openness can flourish in settings that welcome conjecture, but these same conjectures may be silenced if spatial arrangements privilege teacher authority or limit access to communal tools. Such tensions do not indicate pedagogical failure; they reveal how mathematical activity is shaped through competing ecological pressures. Studying these tensions can therefore illuminate how particular environments privilege some forms of participation while holding back others, and how learners navigate these conflicting invitations as they construct mathematical lives. The analytic purpose of MEMaL lies not only in describing each dimension but in examining how these dimensions collide, compromise, and recombine to form the lived conditions of mathematical experience.

Implications: Researching Mathematical Life Ecologically

The MEMaL framework encourages research to examine mathematical life through the environments that sustain participation, reasoning and recognition. This ecological stance treats mathematical activity as emerging through relations among people, tools, discourses, and material arrangements, a view consistent with work that conceptualizes learning as participation in socially organized practices (Cobb et al., 2009; Nasir & Hand, 2008) and as embodied engagement with artefacts and gesture (Arzarello et al., 2009; de Freitas & Sinclair, 2013; Sinclair & Ferrara, 2023). Taking environments as central opens up methodological directions for research concerned with the relational conditions of mathematical participation. A MEMaL-informed analysis can examine how performance, beliefs, affect, and participation take form within wider configurations of mathematical activity.

MEMaL can inform case studies, ethnographies, video-based interaction studies, longitudinal research, and studies tracing mathematical activity across homes, classrooms, workplaces, and community spaces (Civil, 2014; Turner et al., 2024). A central unit of analysis is the ecological configuration: a bounded episode, activity, or trajectory in which spatial, temporal, epistemic, affective, and imaginative conditions become

Table 2. Ecological dimensions of mathematical life

Ecological dimension	What it organizes	How mathematical activity takes shape	Illustrative example	Threats/ constraints	Research opportunities
Spatial	Bodies, tools, visibility, authority	Emerges through embodied interaction, tool use, material layout, and recognition	A carpenter aligns a diagonal cut using muscle memory and a square rather than written measurement; their knowledge remains invisible to observers unless named mathematics. Example inspired by Millroy (1991)	Surveillance, rigid layouts, restricted tool use, filtered visibility	Investigate participation as environmental design; analyze how politics of visibility shapes recognition
Temporal	Rhythms, pacing, repetition, gestural time	Stabilizes through iterative adjustment, rehearsal, waiting, and slow accumulation	A child refines symmetry through repeated folding, but school tasks demand quick answers. Example inspired by Ng and Sinclair (2013)	Standardized pacing, acceleration, timed assessments, “coverage” pressures	Trace nonlinear growth; study recursive, situated tempos instead of linear progression
Epistemic	Criteria of adequacy, credibility, elegance, value	Reflects cultural and local values about what is considered convincing, valid, or worthy	An accountant routinely uses approximation and proportional reasoning to balance multiple invoices rapidly, prioritizing practical accuracy over exact symbolic procedure. Example inspired by Mkhize (2019)	Privileging symbolic proof, Eurocentric norms, exclusion of everyday expertise	Map local criteria of adequacy; foreground everyday practice as epistemic rather than anecdotal
Affective	Belonging, risk, exposure, recognition	Feelings arise through atmospheres that enable dignity, curiosity, and agency	A first-year engineering student fears being seen as struggling with concepts that once felt familiar, and their anxiety grows not from mathematical difficulty alone but from an atmosphere where error signals incompetence. Example inspired by Prahmana et al. (2019)	Shame, comparison cultures, inherited narratives, punitive assessment	Study affect as atmosphere; design for dignity, relational safety, and exploratory risk
Imaginative	Futures, creativity, projection, possibility	Conjecture, modelling, sensory imagination, narrative sense-making	During a geometry lesson, a pupil invents a new rule for generating repeating patterns using rotated paper shapes. Example inspired by Capone et al. (2024)	Restricted curricula, prototype thinking, ability discourses, constrained futures	Investigate imagination as political; examine how mathematical futures are cultivated or denied

consequential through their interrelations. This unit might comprise a classroom problem-solving episode, a sequence of lessons, an interaction with a mathematical tool, or a learner’s participation across connected settings. Researchers can foreground the dimensions most relevant to the phenomenon and evidence under study.

Data collection can make these ecological relations visible. Video, audio, and field notes can document interactions, bodily positioning, tool use, pacing, participation, gesture, repetition, and shifts in atmosphere (Glasnović Gracin & Trupčević, 2022; Ng & Sinclair, 2013). Learner work, photographs, maps of material arrangements, digital traces, and other artefacts can reveal how mathematical activity is organized materially. Interviews and stimulated-recall conversations can illuminate experiences of recognition, risk, credibility, and possibility (Grootenboer & Marshman, 2016; Hannula, 2019). Lesson plans, assessment requirements, schedules, and policy documents can provide evidence of wider organizational conditions.

Analysis moves from identifying relevant dimensions to tracing their configuration. Researchers can reconstruct a focal episode or trajectory, identify consequential conditions, and examine their relations: how spatial organization alters participation, how pacing shapes opportunities for explanation, how epistemic expectations influence affective risk, or how recognition changes what participants imagine themselves able to do mathematically. Epistemic conditions may be particularly significant where criteria for legitimate mathematical reasoning vary across cultural and institutional settings (d’Ambrosio, 1985; Hunter, 2022). Comparisons across episodes, participants, times, or settings can then identify moments of reconfiguration,

in which changes in one condition reorganize others. The analytic emphasis falls on which relations become consequential and what they reveal about the mathematical activity under study.

A MEMaL analysis can proceed through four iterative analytic moves. First, the researcher identifies a focal episode, activity, or trajectory and considers which ecological conditions appear most consequential to the mathematical activity taking place. The five dimensions are used here as sensitizing distinctions rather than as categories that must all be represented equally. Second, evidence can be associated provisionally with one or more dimensions. I do not see these as mutually exclusive categories: an utterance, interaction, artefact, arrangement, or event may speak to several dimensions at once, and these overlaps may themselves point to relations worth examining more closely. Third, the researcher traces how these conditions work together. One may enable or restrain another, amplify its effects, compensate for a difficulty elsewhere, stabilize an existing pattern, or come into conflict with it. These relational interpretations can be developed through temporal sequences, contrasts across episodes or settings, participant accounts, and the convergence of observational, material, interview, or documentary evidence. Fourth, the researcher asks whether these relations themselves change. As noted earlier, I use ecological reconfiguration to describe moments when a shift in one or more conditions changes how other conditions operate, producing a discernible difference in mathematical participation, recognition, credibility, affective experience, or what participants come to imagine as possible. The aim is not to count dimensions, but to understand how their relations come to matter within the mathematical life being studied.

To illustrate how these analytic moves might work in practice, consider a primary-school study following a small group of pupils through a sequence of problem-solving lessons. A classroom video could document positioning, gestures, tools, interaction, and pacing; written work could trace emerging mathematical ideas; stimulated-recall interviews could explore participants' experiences of specific moments; and lesson plans or assessment expectations could reveal institutional conditions. Focal episodes might include a pupil moving from observation to contribution, withdrawing after public evaluation, or adopting a new representation. A MEMaL analysis would trace how spatial arrangements, temporal opportunities, epistemic recognition, affective conditions, and imagined possibilities combine to produce such changes. Comparing episodes could identify which ecological relations carry explanatory significance and how configurations develop over time.

Empirical application marks the next stage in MEMaL's development. Research across primary, secondary, tertiary, workplace, and community settings can examine how ecological configurations become empirically observable, how their relations vary across contexts, and how empirical findings refine the framework.

Limitations of MEMaL

MEMaL is not intended as a complete theory of mathematical learning, but as an analytic framework for examining how spatial, temporal, epistemic, affective, and imaginative conditions become consequential through their configuration. Its usefulness therefore depends on the question under investigation. A MEMaL analysis should do more than identify the presence of one or more dimensions; it should examine how relations among them shape the mathematical activity under study. Where such ecological relations are not central to the phenomenon of interest, other theoretical approaches may offer greater explanatory value. This boundary is particularly relevant to advanced formal mathematics and pure mathematical research. MEMaL may illuminate the conditions within which such work takes place, including disciplinary norms, temporal rhythms, material and symbolic resources, affect, recognition, and imagination. It does not, however, explain the formal validity of a proof, the truth of a theorem, or the mathematical relations through which such validity is established. In these cases, MEMaL is complementary to approaches concerned more directly with mathematical reasoning, cognition, or formal knowledge. The applicability of MEMaL across educational levels and settings also remains an empirical question. Although the framework is developed through scholarship and examples that span school, university, workplace, community, and other settings, the present conceptual paper does not establish how consistently its analytic value will transfer across these contexts. Future research could therefore examine how MEMaL operates in settings such as secondary mathematics and mathematics teacher education, including the extent to which particular ecological relations become consequential across different forms of mathematical activity.

CONCLUDING REFLECTION: MATHEMATICS AS AN ECOLOGICAL FORMATION

Understanding mathematics ecologically involves attending to the conditions through which mathematical activity takes shape. Classrooms, homes, workplaces, and community settings organize spatial arrangements, temporal rhythms, epistemic values, affective atmospheres, and imaginative possibilities that participate in producing mathematical meaning. Political forces operate across and via these conditions, structuring the possibilities through which mathematical participation becomes intelligible, credible, and valued (Gutiérrez, 2013; Pais & Valero, 2012). From this perspective, mathematical experience emerges through the environments that sustain and organize it.

MEMaL's distinctive contribution is to treat the configuration of spatial, temporal, epistemic, affective, and imaginative conditions as theoretically consequential. Mathematical life takes shape through relations among these dimensions, which may reinforce one another, come into conflict, stabilize particular forms of participation, or change. Ecological reconfiguration helps explain why similar mathematical activity may be credible in one environment yet rendered invisible in another, sustainable for one participant yet precarious for another, or imaginable in one setting yet precluded elsewhere. MEMaL therefore offers a relational account of how ecological conditions become consequential within particular forms of mathematical activity.

This relational emphasis also places MEMaL alongside complexity accounts of learning. Complexity theory (Davis & Simmt, 2003; Davis & Sumara, 2005) explains how new possibilities emerge through interactions within adaptive individual and collective systems, while MEMaL directs attention to the ecological conditions through which those possibilities acquire mathematical form, legitimacy, affective significance, and futurity. The resulting shift is from locating mathematical capacity primarily within learners towards examining the mathematical worlds that educational, domestic, workplace, and community ecologies make possible.

This is ultimately the sense in which I understand mathematics as an ecological formation. Mathematics is more than a body of knowledge or a form of reasoning that people carry from one setting to another. It takes shape through the worlds in which people live and participate through relationships, materials, rhythms of time, ways of recognizing knowledge, emotional experiences, imagined possibilities, and the political conditions that organize them. To study mathematical life ecologically, then, is to ask not only what people know or do mathematically, but what kinds of mathematical worlds are rendered possible, who benefit from these, and under what conditions do they become accessible.

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