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REFLECTION ON THE FIELD

Stimming as Thinking: a Critical Reevaluation of Self-Stimulatory Behavior as an Epistemic Resource for Inclusive Education

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Abstract

Peripheral sensorimotor stimming activity, such as rocking and fidgeting, is widely considered irrelevant to and even distracting from learning. In this critical-pedagogy conceptual paper, we argue that stimming is an intrinsic part of adaptive functioning, interaction, and cognitive dynamics. We submit that when cultural resources build from students' own sensorimotor dynamics, rather than subjugating them to hegemonic corporeal norms, learners' intrinsic sensorimotor behaviors may be embraced and empowered as mental activity. This call for transformative inclusive pedagogy is of particular importance for neurodivergent children whose sensorimotor engagements have historically been ostracized as disruptive. Following a conceptual analysis of stimming that builds on a range of neuro-cognitive empirical studies drawing on post-cognitivist embodied cognition theory, we imagine inclusive educational futures that disrupt sedentary instructional design to elevate minoritized learners' sensorimotor activity. As proof of concept, we present an example inclusive embodied activity, balance board math, a pedagogical tool designed to elicit stimming as thinking. We propose a set of design heuristics for realizing stimming's pedagogical potential.

Keywords Embodied cognition · Fidgeting · Instructional design · Stereotypy · Stimming

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Introduction

A symphony of stimming, from twirling pens to tapping toes inside shoes, takes place around and through children's learning, mostly hidden in plain sight. At best, educational research and practice assume this ongoing flow of spontaneous activity to be irrelevant, and at worst a harmful distraction. But are such assumptions sound, given growing evidence for the role of bodily activity in mental activity? What would it mean for learners, especially children currently marginalized for their stims, if their stimming were considered relevant to learning? What could teaching look like that endorses stimming as central and contributing to curricular content learning?

This paper was motivated in the context of an ongoing pedagogical design-based research project, Balance Board Math (BBM), for which the central design conjecture is *leveraging stimming as conceptual cognition*. Analyzing our data led us to speculate more broadly about cognitive science theory, as well as the practice of pedagogical intervention. In this conceptual paper, we put forth a revisioning of repetitive sensorimotor behaviors commonly known in education as stimming. We invite you to rethink with us the axiological ("The Current State of Stimming" section), theoretical ("An Embodied View of Stimming" section), and practical ("Tapping the Untapped: Implications for Instructional Design" section) facets of stimming. For the latter, we use the BBM project as an example context to think about realizing stimming's pedagogical potential.

We argue that educational psychology requires a theory of stimming that:

a) recognizes neurodivergent testimony of their sensory experiences and practices;
b) models the actual and possible functions of stimming, including self-regulative, communicative, and cognitive functions;
c) informs transformative pedagogical reimaginings of how stimming could be endorsed and centered in learning activities.

Grounded in this theoretical perspective, we illustrate how stimming might be *instrumented* (i.e., functionally extended) through furnishing opportunities for stimulation, *interactional* (socio-ecologically) as a productive resource for communication and shared sense-making, and *instrumentalized* (i.e., contextually applied) as epistemic actions in direct interactions with digital education resources.

The Current State of Stimming

We begin with an overview of how the sociobiological phenomenon of stimming is understood, first in education norms and pedagogical practices, and then within research literature.

Questioning the Status Quo

Classroom Norms

It is a widely accepted norm that the vast majority of academic learning today is a sedentary affair. One might characterize the status quo (a literal Latin *status*, or position) to be sitting with both feet on the floor, hands at rest, gazing frontward. Such posture is imagined to reflect attentive studenthood, and indeed, is used as a measure of engagement in learning analytics (e.g., De Carolis et al., 2019). We problematize this status quo for all people, attending in particular to the experiences of neurodivergent[1] people (Walker, 2021) whose neurology leads them to act in ways that often transgress such norms. Whereas the neurotypical majority are able to get by under the status quo, neurodivergent experience reveals possibilities for educational practice that could open new potential for everyone.

Anthropologist David Howes (2022) writes, "[P]eople are positioned differently—sensorially, socially—in accordance with the prevailing sensory regime" (p. 327). Individuals' sensory neurology, including their sensitivity to sensory stimuli (Dunn, 1997; Jagiellowicz et al., 2011) and sensory integration profile (Lane et al., 2019), impacts their experience of academic environments and norms. For example, low sensitivity to sensory input is associated with *sensation-seeking* behavior: actively pursuing greater levels of sensory stimulation through activity such as stimming (Dunn, 1997). Many learner groups currently tracked into special education, including those on the autism spectrum (Kadlaskar et al., 2022) and those with ADHD (Fabio et al., 2024), exhibit atypical sensory profiles.

Greater sensory atypicality has been associated with lower academic performance (Ashburner et al., 2010). We propose that these challenges are a reflection of the unsuitability of common cultural infrastructures, practice, teacher training, and norms to accommodate the full diversity of sensory profiles, rather than some inherent pathology (Tancredi, 2024). By analogy, some left-handed people, including one of the authors, struggle to cut through paper with standard scissors, not due to any inherent motor challenges, but rather due to the design features of scissors designed by right-handed people that assume right-handed use. The blade angle of right-handed scissors *creates* apparently motor-challenged lefties. If the environment were to accommodate lefties' bodily engagement, as with neutral or left-handed scissors, we could engage with the same acuity. This trivial instance exemplifies the way that exclusionary design can generate needless challenges. At a systemic level, neurodivergent students find that classrooms do not meet their sensory needs. Furthermore, when students engage in sensory activity such as stimming to meet these needs themselves, these bodily expressions can be subject to discipline (i.e., Annamma, 2017). Indeed, autistic individuals often report the need to suppress or substitute

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[1] Analogous to biodiversity, variation in human neurology is referred to as *neurodiversity* (Walker 2021). The terms neurodiversity, neurodivergent, and neurotypical originated from the autism rights movement and have been taken up in discussion of people with other neurotypes, such as ADHD and dyslexia.

their stims for social acceptability (Charlton et al., 2021). If stimming is frequently defined as task irrelevant, and ill suited to the setting, perhaps it is the academic task and setting that must change.

Thus, in mainstream education, as in neurotypical society more broadly (Kapp et al., 2019), neurodivergent individuals are stigmatized for their inclination toward sensory exploration through movement. The dominant sensory regime reifies sedentary studenthood through environment and tool design, language (Nolan & McBride, 2015), and norms that collectively desensitize us to other forms of sensorial exploration. What might education look like if instead, the full range of sensorial explorations were embraced?

Epistemology and Instructional Practices

We turn, now, to the questions of disciplinary knowledge. Historically, stimming has been seen as unrelated to the disciplinary practices that shape thinking and knowing. However, our present cultural resources evolved through the collective, distributed, and iterated efforts of individuals who had privileged status, power, leisure, and access to engage in academic disciplinary practices such as mathematics (Tanswell & Rittberg, 2020). In so doing, each adapted environments and artifacts to their cognitive preferences, just as historical urban architecture features such as stairs privilege the ambulatory individuals who created them (Goldsmith, 2007). The resulting disciplinary approaches implicitly privilege dominant groups' skills and orientations, such as the cognitive styles and skills associated with males in the field of computer science (Turkle & Papert, 1990). Whereas neurodivergent people have always been present, due to their minoritized status, their profiles and likelesses did not always enter the equation in formulating the arena for what became normative disciplinary praxis. The world as we know it was created largely for neurotypical folks, including academic disciplines. We must surface ableist prejudices resulting from a history of sequestered discourse, where sensorially pluralistic perspectives have been covert or all too absent.[2]

How might sensory experience shape epistemology? Let us begin with the example of a student who has been blind from birth's understanding of triangles. She has never seen a triangle, but she knows what they are. Her way of knowing triangles resists the tendency in mathematics to implicitly define geometric shapes' features visually. The implicit oculocentrism of the mathematics field yields pedagogical practices that make geometry less accessible for her: triangles are taught with images such as diagrams, which are created visually, then described to her with language (Abrahamson et al., 2019). Special education embodied design (SpEED), a design-based research framework for inclusive design grounded in embodied cognition, calls

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[2] Given our critique of neurotypicality's pervasiveness in research and practice, a note on author positionality and approach is warranted. One author is sensory neurodivergent; both authors have engaged in extensive reflexivity work on their own neurodivergent traits (e.g., agnosias) and forms of stimming. Acknowledging stimming's importance in autistic embodiment and culture in particular, we cite autistic authors as thought leaders, and we encourage our readers to pursue work by autistic scholars, advocates, and poets. We thank an autistic scholar we admire for her review of this manuscript prior to peer review.

this an instance of *modalism* (Tancredi et al., 2022a) in that privileging the dominant modality of vision changes how our learner gets to interact with the concept at hand. SpEED differentiates the sensory and motor systems engaged, such as vision (*modality*), materials, such as printed textbooks (*media*), and system of meaning making, such as diagrams and language (*semiotic mode*) of instructional designs and highlights their interrelation. Rather than build from the blind student's experiences in modalities she has access to, such as touch and proprioception, she is presented an onslaught of verbal language describing experience in a modality to which she does not have access. SpEED calls for equitable instruction to offer her experiences rooted in modalities through which she explores the world, for example, by teaching with tangible manipulatives (i.e., Lambert et al., 2022). Analogously, highly sensation-seeking learners require greater stimuli intensity to regulate and attend, and stimming is an explicit part of their exploration, yet our teaching methods and norms present concepts in static formats and penalize spontaneous movement.

Thinking and stimming have historically been categorized as fundamentally separate processes. However, we propose that if stimming appears incongruous to ongoing constructive/cognitive engagement, this is not a biological necessity. Rather, the artifacts and activities of neurotypical people have precluded the explicit blending and hybrid functioning of these neurocognitive systems. It is insufficient, and indeed, rooted in ableist assumptions, to propose that stimming be addressed such that learning can occur. Instead, the underlying intertwinement of stimming and thinking, masked by modern, western, neurotypical-centric practices, must be reclaimed.

Research Orientations

As with classroom norms and instructional practices, education research's theorization and treatment of stimming are infused with sociohistorical positionalities we argue are problematic in that they were heavily developed by neurotypical researchers who brought to bear their own normative sensory assumptions. Historically, work on stimming and learning has characterized stimming as deleterious and studied means of its extinction. Grounding in behaviorism, researchers used punishment, including such measures as "slapping the subject briskly on the hands when he began to engage in self-stimulatory behavior" (Koegel & Covert, 1972, p.383), to suppress stims in favor of learning outcomes such as pressing a button at desired times. Such work has been critiqued as neurotypical conversion therapy, ignoring the purpose and lived experience of stimming, and suppressing intrinsic autistic ways of being (Wilkenfeld & McCarthy, 2020), yet is still cited today to describe the relationship between stimming and learning.[3] Psychology has evolved beyond

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[3] We acknowledge that some forms of stimming, such as head banging, can cause harm to an individual. Nevertheless, we argue that understanding what an individual is experiencing when engaging in such stims and understanding the broader functions of stimming in context are necessary to appropriately respond to such stims.

behaviorism—it is ethically and theoretically imperative that educational models and approaches to stimming evolve, too.

A Stim by Any Other Name

We aim to reevaluate the constitution, function, and normativity of stimming, reinterpreting, and building upon prior perspectives within and beyond the cognitive sciences. We begin by summarizing the many ways spontaneous background activity has been theorized across different research contexts and clinical fields (Box 1). We highlight overlaps between the construct of stimming with the constructs of stereotypies and hyperactivity (psychiatry), fidgeting and displacement behavior (psychology), embodied self-regulation (human–computer interaction), sensation seeking (occupational therapy), and nonverbal adapters (communication-studies) (Box 1).

Box 1 Spontaneous background activity terms

Stimming: Psychiatry term used in diagnostic criteria for autism and autistic community term, abbreviation for “self-stimulation”: repetitive actions, such as physical movements or vocalizations

Hyperactivity: Psychiatry diagnostic term denoting movement considered to be excessive and not fitting to the setting, as part of the criteria for ADHD

Stereotypies, tics, punding: Medical terms for patterned, repetitive movements

Sensory/sensation seeking: Occupational-therapy term for the activity of obtaining sensory input for self-regulation through actions such as bodily movement. Also used to describe individuals who engage in such activity to a high degree

Embodied self-regulation: Human–computer interaction term for managing attention and emotion through physical activity

Fidgeting: Psychology term for repetitive body movements, generally characterized as task irrelevant, involuntary, and superfluous

Displacement behavior: Psychology term for activity such as face touching, scratching, and lip biting, associated with feelings of anxiety and stress

Adapters: Communication-studies term for a category of nonverbal communication kinesics wherein actions first learned as part of need satisfaction, managing emotions, interpersonal interaction, or instrumental learning are partially or fully completed

Stimming semiosis: Semiotics term to describe stereotypic movement as autistic semiosis, wherein the body is both index and sign for sensory significations

These constructs differ along several key axes, the first of which is focal population. Medical constructs such as stereotypy and hyperactivity are applied specifically to those with medical diagnoses and are often used as defining features of a given diagnosis. Medical research categorizes patterned, periodic movements and utterances associated with defined medical conditions as *tics* (variable-frequency), *stereotypies* (clustered, repetitive rhythmic sequences), or *punding* (prolonged, complex stereotypy) (Nilles et al., 2023). Thus, the behaviors in question are by definition contrasted with an imagined norm and presumed to be, to some degree, pathological and, often, in need of remediation. In psychiatry, stereotypy is part of the diagnostic criteria for autism of “stereotyped or repetitive motor movements’’ (American Psychiatric Association, 2013), theorized as a form of self-stimulation, or *stimming*. Movement that is considered excessive or ill fitting to the setting, whether repetitive or not, is considered *hyperactivity*, part of diagnostic criteria for attention hyperactivity deficit disorder (ADHD) (American Psychiatric Association, 2013). In response to this pathologization, critical scholars and neurodiversity advocacy groups (e.g., Loud Hands Project Autistic Self Advocacy Network (ASAN), 2012) have reclaimed the medical term "stimming," celebrating stimming as an expression of autistic embodied experience and identity, not only self-regulatory but also political, aesthetic, and communicative (Felepchuk, 2021; Nolan & McBride, 2015). Other repetitive motor action constructs are studied in the general population. For example, psychology defines *fidgeting* as task irrelevant, peripheral, involuntary, and superfluous repetitive bodily movements (see, for example, Mathis, 2019; Ricciardi et al., 2019).

Constructs in other fields presume different functions for peripheral motor behaviors. In human–computer interaction, they have been theorized as a form of *embodied self-regulation* to manage attention and emotion (Karlesky & Isbister, 2016). Such a view resonates with occupational therapy models, which conceptualize stimming as *sensation seeking*: pursuing sensory stimulation for the purpose of self-regulation. For example, rocking back and forth offers stimulation of the sense of balance, theorized as a means of modulating arousal by either calming or alerting the nervous system (e.g., Lane et al., 2019). As such, the mind and body are viewed as spontaneously acting to achieve desirable levels of stimulation. Other functional views of repetitive motor action include *adapters* in communication studies: nonverbal communication kinesics theorized to express internal states such as arousal and anxiety, similar to psychology's construct of *displacement behaviors* (Mohiyeddini et al., 2015). Stimming has further been positioned as semiotic, constituting autistic sensory utterances in which "the body and its sensory apparatus function as both index and sign systems that hold these together" (Connolly, 2008, p. 242, as cited in Nolan & McBride, 2015).

Another key distinction in the literature is that some constructs (hyperactivity, fidgeting) are explicitly limited to overt motor behavior, whereas others (stimming, embodied self-regulation) include stimulatory behaviors and experiences more broadly, including such activity as humming, vocalizing, or wearing heavy clothing or jewelry. Furthermore, some presume that behaviors are subconscious (such as fidgeting), whereas others (such a stimming semiosis) include conscious activity as well.

Given these differences among constructs, we elect the term "stimming" in this paper due to its conceptual congruence with embodied perspectives and axiological resonance with inclusive education. In our usage, stimming is spontaneous, repetitive, often rhythmic activity that provides sensory stimulation. While stimming is often overt motor action, it includes covert stimulatory behaviors as well (we discuss this further in light of our theoretical framework in the subsequent section). The term stimming also spans both subconscious and conscious behaviors,[4] relevant as we probe stimming's pedagogical potential within contexts of reflection on action. Additionally, the term stimming foregrounds the function of seeking self-initiated sensory stimulation, which we find highly relevant to an analysis of embodied action. Finally, this

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[4] By self-report, stimming often begins as subconscious, but may consequently become conscious and intentional (Kapp et al., 2019).

term is used to depathologize a broad range of behaviors within neuroinclusive dialogue, resonating with a goal of inclusive education. Although we take as our focal population the full spectrum of the general population, we propose that building from work on those who are presently marginalized for their stims bolsters more robust theory, toward more inclusive practice.

An Embodied View of Stimming

4(ish) E Cognition

Cognitivism, the dominant paradigm in the cognitive sciences beginning in the latter portion of the twentieth century, modeled thinking as the mental processing of information through logical manipulations of amodal symbolic propositions (i.e., Fodor, 1975), couched within an implicit mind–body Cartesian dualism. This view offers little purchase on the purported exploratory function of stimming described by neurodiversity scholars (Nolan & McBride, 2015). However, in recent decades, this view has been critiqued for its separation of mind and body, giving rise to embodied cognition theory, which posits that thought is constituted in ongoing sensorimotor adaptation to the environment in ways that serve our organismic and cultural needs (Varela et al., 1991). This post-cognitivist paradigm offers a theoretical framework to integrate autistic people's descriptions of stim explorations into models of cognition. Post-cognitivism foregrounds the role that the nature and activity of our bodies plays in cognitive processes (Gallagher, 2005; Newen et al., 2020). With its focus on interaction, we propose that post-cognitivist theory offers an alternative conceptualization of stimming as part of the cognitive system's dynamic interactions, through the body, with the physical and social environment.

Post-cognitivism is often characterized with a set of interrelated E adjectives referred to as "4E cognition" (Fig. 1): cognition as *embodied*, *enacted*, *embedded*, and *extended* (Newen et al., 2020); sometimes further specified as *ecological* and *emotional* (i.e., Troncoso et al., 2023).[5]

In the following subsections, we review and reinterpret existing literature on stimming from a post-cognitivist perspective, introducing each E adjective in sequence and drawing evidence from research on stimming and related constructs (Box 1) to analyze how this dimension of cognition may inform an integrative picture of stimming in cognition. We use this structure to circumscribe stimming from a post-cognitivist perspective, acknowledging the inherent overlap of the respective Es.

We put forth five precepts for a multi-E model of stimming as (1) an *embodied* cognitive processes that impact thought and cognitive load ("Stimming as Embodied" section); (2) an *enactive* substrate for complex actions and concepts ("Stimming

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[5] There remains some contention among post-cognitivist theorists, who endorse Es to different extents and disagree on topics such as mental representations. And yet, these perspectives cohere in highlighting that cognition arises through an agent's interaction, through a body, with their physical and social environment.

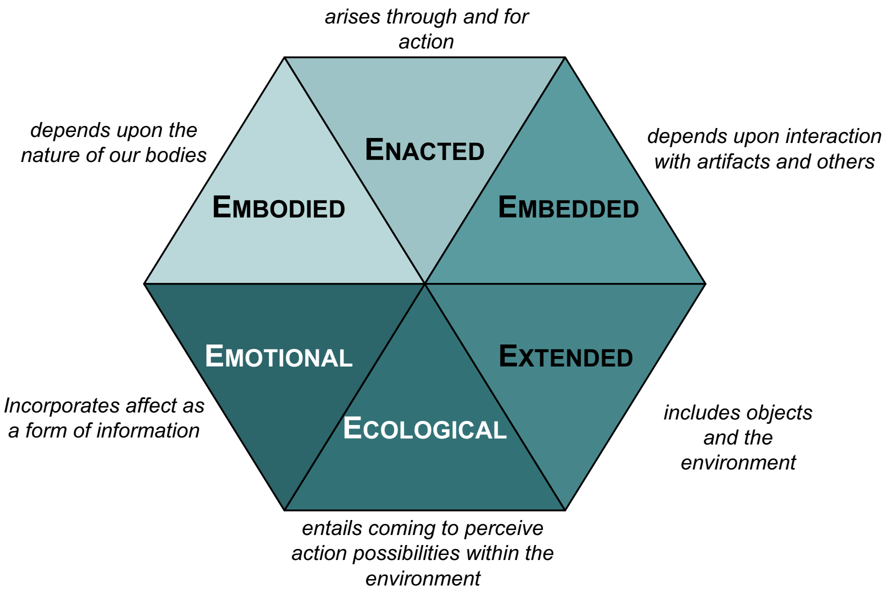

Fig. 1 Qualities of cognition, per post-cognitivist perspectives

as Enactive" section); (3) *embedded* and *emotional:* reflecting and regulating cognitive–affective system dynamics ("Stimming as Embedded" and "Stimming as Emotional" sections); (4) *ecological:* responding to properties of the physical and cultural environment ("Stimming as Ecological" section); and (5) an *extended* cognitive resource that functions as socially communicative ("Stimming as Extended" section).

Stimming as Embodied: Influencing Thought and Lightening the Load

"Knowing is bound to the world through the body" (Smith, 2005, p. 279). Embodied cognition, inspired by phenomenological philosophy, foregrounds the inherent sensorimotor qualities of cognitive activity (Varela et al., 1991) and, in so doing, melts the ontological boundary between overt and covert sensorimotor activity. Cognitive processes, such as language comprehension, covertly implicate the motor system: for example, hearing the words "kick," "pick," and "lick" triggers neural activity in and adjacent to the motor and premotor areas activated when moving the leg, arm, and face, respectively (Hauk et al., 2004). Just because others cannot hear or see something does not mean it is not a subjectively real—even intense!—sensorimotor experience. From this perspective, *overt* forms of stimming (fidgeting with a pen, pacing, humming), *discreet* forms (twisting a ring, biting one's cheek, tapping toes inside a shoe), and entirely *covert* forms (audiating a Mahler symphony in one's head) might all bear similarities in the stimmer's phenomenological experience. An embodied perspective, then, brings together work on internal stimulatory activity such as earworms and external movement such as fidgeting.

Bodily processes, down to our very breathing, affect cognition (Varga & Heck, 2017). Awareness increases when breathing in, such that stimuli presented during an inhale are recalled more accurately than those presented during an exhale (Perl et al., 2019). Our perception of time expands and contracts in keeping with our heartbeat (Arslanova et al., 2023). Additionally, background motor activity impacts speech: when asked to move marbles while telling a story, people are more fluent when the direction of movement aligns with their speech, such as moving them upward while describing rising temperatures, than when background movement and speech are incongruent (Casasanto & Lozano, 2007). Furthermore, right-hand squeezing a ball or walking while thinking increases creativity (Goldstein et al., 2010; Oppezzo & Schwartz, 2014). Even imagined actions can affect perception: for example, imagined body motions can induce nystagmus eye movements and changes in vestibular stimuli perception (Mast et al., 2014). All of these sub-conscious, semi-conscious, backgrounded, or covert bodily phenomena influence thought. Stimming ought to be presumed relevant as well.

Let us entertain the view, as assumed in many classrooms, that the impact of stimming on thinking is counterproductive. After all, adding parallel physical or mental tasks is theorized to add to an individual's *cognitive load*, adversely affecting cognitive performance. Cognitive load (Sweller, 1994) denotes the working memory resources taken up by a given task. Even acts as simple as standing can compete for cognitive resources (Ruffieux et al., 2015). One might suppose, then, that stimming adds to cognitive load, adversely affecting performance of a primary task. However, if this were the case, the finding that stimming actually *increases* in the face of high cognitive load may be surprising. Fidgeting, for example, increases with sustained effort on a task (Farley et al., 2013) and when reading more boring texts (Witchel et al., 2016). Does stimming indeed compete for learners' physical and attentional resources? If so, why might such a deleterious process have persisted throughout evolutionary history?

We might find a fruitful analogy in work on another bodily process: gesture. In contrast to other parallel activities, gesture has actually been found to *reduce* cognitive load (Risko & Gilbert, 2016). Gestures congruent with thinking, such as tracing, support working memory (Sepp et al., 2019). Gesture has a facilitatory role in tasks such as problem solving: children told to gesture when solving math problems generate more problem-solving strategies, and ultimately solve more problems (Broaders et al., 2007). Conceptual gestures emerge from hands-on, instrumental action (Streeck, 2021) and offer a means to activate, manipulate, package, and explore spatio-motoric information for speaking and thinking (Kita et al., 2017). Inhibiting gesture exacerbates difficulty resolving word retrieval issues, particularly those with limited verbal short-term memory (Pyers et al., 2021), and leads people to perform worse on memory tasks (Goldin-Meadow et al., 2001), suggesting that the act of limiting gesture itself may even require cognitive resources. Working memory generally exhibits fewer limitations when learning "biologically primary information" of relevance in our evolutionary past, such as movement, than when learning cultural knowledge, such as reading (Paas and Sweller, 2012). Bodily activity such as gesture and stimming, then, may leverage evolutionarily foundational human capacities.

Might stimming, too, lighten the load? Several findings suggest the plausibility of such a phenomenon. Analogous to findings with gesture, autistic adults self-report that the act of *suppressing* stimming requires cognitive resources (Charlton et al., 2021). Additionally, in boys with ADHD, increased hyperactivity during working memory testing is associated with improved performance (Sarver et al., 2015). In neurotypical adults, stims like doodling improve auditory recall (Andrade, 2010). How might stimming achieve such an impact? A conservative explanation is that stimming's impact on arousal mediates its impact on cognitive performance. A bolder explanation is that, just like gesture, stimming is part of cognition itself.

Stimming as Enactive: a Substrate for Developing Complex Actions and Thoughts

A view of cognition as *enactive* highlights that cognition evolved for action. As such, perception and action unfold together. Repeated sensorimotor patterns of perceptually guided action give rise to cognitive structures (Varela et al., 1991). In education, this view of cognition as enactive has been applied to show that students can ground mathematical notions by learning to move in a new way that consequently takes on conceptual significations (Abrahamson & Bakker, 2016).

Given that stimming is part of an individual's action manifold, we submit that enactivism suggests the relevance of stimming to the development of new perceptual orientations. That is, stimming constitutes a form of action that might impact cognitive structures, which are in turn the basis for conceptual learning. Or reciprocally, if perception guides all motor activity (Mechsner, 2004), then stimming, too, must be affected by, and affect, an individual's perception. Consistent with this view, features such as the presence of a visual music video impact how much people stim when listening to a song (Witchel et al., 2016), suggesting that sensory features of a task shape concurrent stimming. We will focus, in developing this view, on two areas where the relationship between stimming and cognitive structures is especially clear: stimming's function in infancy and rhythm in cognition.

Stimming as the Foundation of Functional Motor Behavior

Infant studies have found that stereotyped movements play a key role in early motor skill development. Simple repetitive behaviors, such as arm waving and body rocking, are observed to precede goal-directed complex motor behaviors that use the same body segments (reaching and crawling) (Thelen, 1979). For example, repetitive, patterned arm movements precede effective infant reaching; the amplitude and timing of these movements are modulated toward accurate reaching patterns (Thelen et al., 1993). Additionally, infants who received less stimulation to the vestibular sensory system from caregiver actions, such as rocking or bouncing, engage in more stereotyped movement themselves (Thelen, 1980). These ontogenic findings suggest a view of stimming as core to developing and refining skilled action: "simple, stereotyped motor behavior in infants is the foundation on which complex, functional behavior is built" (Shafer et al., 2017, p. 2). Stimming can thus be characterized as foundational to functional motor action.

Stereotypy's functional role is characterized as specific to early development (Shafer et al., 2017). However, this is based on a neurotypical developmental trajectory within the current designed environment. Nolan and McBride (2015) argue that science must move beyond assumptions of *sensory periodization*, whereby sensory exploration is valued in early childhood but expected to be outgrown and replaced with social/cultural signs and symbols. They highlight the ongoing role of stimming in autistic ways of being and making sense throughout development. Stimming could ostensibly continue to offer a basis for developing complex motor development throughout the lifespan, if embraced as such.

Rhythm and Thinking

> "The better we understand the biological basis of rhythm, the better we will be able to employ rhythm—in all its guises—to improve communication and to better understand ourselves." (Kraus, 2021, pp. 218–219)

Surveying the field's state-of-the-art understanding of neural oscillatory activity, Buzsáki (2006) prefaces, as follows, his book titled *Rhythms of the Brain*:

> [B]rains are foretelling devices, and their predictive powers emerge from the various rhythms they perpetually generate. At the same time, brain activity can be tuned to become an ideal observer of the environment, due to an organized system of rhythms. … The notion that oscillators or "central pattern generators'' are responsible for the coordination of motor patterns, such as breathing and walking, is old and well accepted in neuroscience. But the tantalizing conjecture that neuronal oscillators can be exploited for a plethora of other brain-generated functions, including cognition, is quite new and controversial. (pp. vii–viii)

Buzsáki (2006, p. 114) proceeds to demonstrate how multiple neural oscillators coordinate operations within and across neuronal networks to form a hierarchical system in the cerebral cortex. Even consciousness itself, scholars surmise, could be theorized as emergent from the rhythmic neural activity. More recently, a *rhythmic theory of attention* has been proposed by Fiebelkorn and Kastner (2019), who cite their neuroscientific experimental studies to evidence how rhythmic neural activity shapes sensory and motor aspects of goal-oriented engagement with the environment, such as in searching for particular features. As Basso et al., (2021, p. 2) sum this up: "…brain-body connectivity is bidirectional: oscillatory rhythms in the brain drive movement and movement drives oscillatory rhythms."

The bidirectionality of motor–neural rhythmic induction may explain observations by learning scientists that students solving movement-based mathematics tasks spontaneously organize their physical actions into repetitive spatial–temporal patterns, which Palatnik and Abrahamson (2018) characterize as tacit goal structures within their interactional inquiry. Put simply, if we are expected to do some new repetitive job with stuff in the world, we try to encapsulate the task as a recurring sequence of perceptuomotor actions, presumably so as to minimize the allocation of cognitive resources (see also Schack & Mechsner, 2006). Such observations have turned the attention of educational scientists to the rhythmicity of mathematical activities (Bautista & Roth, 2012; Radford, 2015; N. Sinclair, 2018). More generally, sensorimotor activity is inherently spatiotemporal. Time serves as an implicit organizing modality of sensorimotor bio-anatomical interaction with the environment—the very patterns that, per Varela et al. (1991), enable action to be perceptually guided. This principle of learning as *developing spatiotemporally patterned sensorimotor activit*y should obtain whether actions are performed overtly on material features of the environment or covertly on imagined objects (Ingram et al., 2022), whether these actions are the performance itself or a form of simulation (Kirsh, 2010), whether the objects in question are material or symbolic (Landy & Goldstone, 2007), and whether the agent's intentionality is enacted directly or semiotically mediated (Shvarts & Abrahamson, 2023).

Beyond its intrapersonal organizational function, rhythmicality emerges spontaneously as regulating interpersonal joint action—when two or more agents are to coordinate their behaviors, it is advantageous to fall in step with each other (Sebanz & Knoblich, 2009; in mathematics education, Nemirovsky et al., 2013; Abrahamson et al., 2022). Basso et al. (2021) conjecture, therefore, that rhythmicality spans the biological gamut of cellular, neural, sensorimotor, cognitive, and social behavior. Interpersonal generation of rhythmic joint actions could serve also as a semiotic resource for prospectively indexing common referents, enriching a milieu's multimodal linguistic repertory (see, for example, co-operative action, per Goodwin, 2013).

What might all this mean for a functional interpretation of stimming? One hypothesis in neurology research is that rhythmic brain activity from stimming entrains brain rhythms to enhance information processing (McCarty & Brumback, 2021). From an enactivist perspective, our ecological inclination to perform rhythmically repetitive motor actions as a form of regulating our grip on the world suggests that stims, as temporally iterated actions, themselves afford meaningful engagement, even if these meanings are obscured from an observer. For example, an anonymous autistic person eloquently described how rhythmically moving his hand forms the rhythm of his internal monologue, helping to sequence it (Kapp et al., 2019, p.1786). That is, the rhythmic activity of stimming can constitute a means of making sense of the world through thought.

Stimming as Embedded: Cognition as a Dynamical System

The theoretical notion of embedded cognition disrupts the presumed functional hierarchy between peripheral and central components of the cognitive mechanism. In particular, *complex dynamic systems theory (DST)* models cognition as a self-organized (rather than centrally controlled) dynamic system in flux that is dynamically reconfigured as it adapts to act within the ecology (Richardson & Chemero, 2014). In this view, the dynamically stable cognitive system can be perturbed by even low-level microinteractions, pushing it to transition into a new dynamically stable state, requisite for motor and cognitive development (Smith & Thelen, 2003). From a complex dynamical systems view, the cognitive system is made up of numerous elements that are embedded within and open to the environment (Smith & Thelen, 2003). Through interaction, these elements self-organize to form emergent coordination.

The peripheral bodily activity of stimming can be construed as an interactive element of such a dynamical cognitive system. In complex systems, it is the interactions among all the elements that give rise to emergent dynamics: “no single element has causal priority” (Smith, 2005, p. 278). As such, stimming is as much a part of emergent cognitive coordination as central elements like the brain. The chaotically repetitive patterns of stimming should be endorsed as an analytically insightful constituent of the cognitive system’s overall dynamics.

Consistent with this perspective, research shows that higher-level cognitive processes are reflected in bodily activity: mind wandering is associated with an increase in non-instrumental movements (Carriere et al., 2013; Dias da Silva et al., 2022). Mind wandering has been reevaluated from an embodied perspective as enriching cognitive processes underlying task efficacy (Trasmundi & Toro, 2023). For example, in the context of reading, the most effective approach may not be to read at a constant fluent rate, but rather to multi-actionally draw upon goal-oriented reading and complementary mind-wandering processes (Trasmundi & Toro, 2023, p. 6):

> Increasing or lowering the cognitive control over thoughts and modifying the environment in ways in which seems fit to the demands of the activity at hand are embodied processes that encompass the nervous system, the body, and the environment in which a person is embedded.

Stimming, then, can express and impact the state of the overall cognitive system as it dynamically couples and recouples with the environment.

Stimming as Emotional: Reflecting and Regulating System Dynamics

Recasting stimming as part of a complex dynamical cognitive-affective system, we recognize the prospective functionality of stimming in supporting and maintaining that system within a desirable homeostatic, dynamically stable attractor state (e.g., Kelso, 2000). Such a view is consistent with occupational therapy models of stimming as seeking an optimal level of sensory stimulation to regulate arousal (e.g., Dunn, 1997; Geissler et al., 2014). Autistic[6] and non-autistic adults self-report that stimming/fidgeting helps to release excess energy and emotion (Kapp et al., 2019), manage overwhelming sensory environments and noisy thoughts (Kapp et al., 2019), maintain balance and concentration (Charlton et al., 2021), and support focus

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[6] We use identity-first language here in respect of preferences expressed by a majority of autistic adults (J. Sinclair 2010; Taboas et al., 2023), but acknowledge and respect that language preferences are not homogeneous.

and optimal arousal (Karlesky & Isbister, 2016). Supporting this view, stimming increases when access to sensory stimulation is limited, such as when an infant is confined to a playpen or chair (Thelen, 1980), and is reduced in contexts providing ample stimulation, such as exercise (Liu et al., 2015). Animals in captivity have likewise been observed to stim, particularly when understimulated by their environments or lacking their regular dosage of exercise (Davis et al., 2004). Furthermore, stimming affects the balance of activity in the sympathetic "fight or flight" nervous system and the parasympathetic "rest and digest" nervous system (Lane et al., 2019). In addition to alertness, stimming may regulate emotional state. Sensation activates brain networks that produce emotional responses (Rodriguez & Kross, 2023). In particular, displacement behavior is inversely related with stress, suggesting stimming may help with stress regulation (Mohiyeddini & Semple, 2013), consistent with self-reports of stimming supporting calm and pleasure (Karlesky & Isbister, 2016).

Stimming, then, interacts with the nervous system and brain to modulate arousal and emotion. These, in turn, affect cognitive processes such as learning, judgment, and memory (Storbeck & Clore, 2008). In sum, stimming expresses cognitive dynamics and can be understood as dynamically supporting adaptive human cognitive system function.

Stimming as Ecological: Elicited by the Physical and Cultural Environment

A view of cognition as *ecological* (rooted in *ecological psychology*, Gibson, 1966) conceptualizes perception in terms of *affordances*: patterned perceptual information in the environment experienced as opportunities for action (Gibson, 1966). Motor actions respond to perceived environmental invitations (Heft, 1989). This perspective can shed light on the presumed-peripheral activity of stimming, suggesting stims might be solicited by qualities of the environment presented to an individual. We propose that, given stimming's functional role, agents can perceive stim affordances in their environments. For example, a hard surface might afford rhythmic tapping, whereas a malleable object might afford squeezing. The type of sensory stimulation offered by interaction with an object or environmental feature would determine its efficacy in supporting self-regulation.

From early life, different types of movement differentially affect arousal: for example, rocking infants intermittently and vertically promotes bright-alert behavior, whereas rocking them continuously and horizontally promotes drowsiness (Byrne & Horowitz, 1981). Additionally, input to the somatosensory senses including proprioception, tactility, and vestibular function, as well as rhythmic movement, play a crucial role in nervous system regulation (Dahl Reeves, 2001; Lane et al., 2019). The objects available in the immediate environment, such as a pen, and their sensory features, such as the pen's weight and length, invite possible movements, such as twirling, clicking, or tapping (Karlesky & Isbister, 2016). For example, the rhythm of a ventilation system might affect that of a fidget (Drew et al., 2019), or a recently heard song might spark a later earworm (Arthur, 2023). Stimming is elicited by features of the environment that offer up opportunities for regulatory sensorimotor activity.

Stim forms are further shaped and constrained by an individual's personal and cultural history and intrinsic dynamics. Individuals favor different forms of fidgeting contingent upon their emotional state: squeezing when angry, versus clicking, pressing, or tapping when bored (da Câmara et al., 2018). Furthermore, two individuals presented with the same stimuli may stim differently. For example, people engage in more non-instrumental movement when listening to a favorite song than to other music (Witchel et al., 2016). Personal meaning adds a dimension to stims: for example, fidgeting with a wedding band may also carry the reminder of a loved one (Karlesky & Isbister, 2016). Cultural norms can act as additional constraints upon stim possibilities and add layers of meaning to repetitive action. For example, repetitive motor actions, such as rocking and touching beads, have a long history within spiritual and contemplative practices like prayer. Stim forms are thus imbricated in *embodied semiosis* (Nolan & McBride, 2015), wherein the body is the nexus of lived and cultural experience.

Stimming as Extended: an Intercorporeal Resource for Interaction and Communication

The idea of extended cognition highlights cognition as inclusive of objects (Clark & Chalmers, 1998) and even other people (Gallagher, 2013). Stimming has been historically approached as an individual behavior serving an intrapersonal regulating function (if, indeed, granted a function), whereby repeated vocalizations and/or motor actions constitute a multimodal soliloquy. However, advocates in the autistic community and critical autism scholars, grounding within autistic sociality (Milton et al., 2022), propose stimming to be an intrinsic expression of embodied autistic semiosis (Nolan & McBride, 2015). Stimming thus offers a prospective way of being with others that is communicative and socially valuable (Bakan, 2014). Stimming in the presence of other people, then, may also serve an interpersonal expressive function, whether this function is premeditated or emergent.

Per the *ethnomethodological approach to conversation analysis* (EMCA, e.g., Mondada, 2014), conversing individuals use a variety of culturally established multimodal utterances and kinesics, including speech, gesture, face movements, posture, eye contact, and a range of semiotic actions in any medium (e.g., doodling), to manage turn taking while maintaining an apparent interpersonal consensus of common ground. We put forth stimming as one such multimodal utterance. Researchers of non-speaking autistic individuals have drawn on conversation-analysis and co-operative action methodologies to demonstrate that stimming can serve as an interactive resource for engaging in collaborative joint action (Chen, 2016, 2022; Dickerson et al., 2007). For example, Dickerson et al. (2007) found that autistic children responding to math questions effectively used repeated tapping on focal objects such as flashcards to display their active engagement and to indicate upcoming talk. Chen (2022) found that autistic children's stims could become the substrate for co-constructed, improvisational interaction with caregivers. Conn (2015), in analyzing autobiographies of autistic authors, identifies a sensory and body-based *autistic intersubjectivity* whereby "people are physically attuned to each other, act in synchronicity and enjoy each other's presence, but carry out interaction in non-face-to-face and largely non-verbal ways" (p. 1202). As such, stimming could be viewed as a broadly valuable means for social participation in cultural practices, wherein two or more individuals partake in coordinated intercorporeal enactments.

Indeed, some forms of stimming are morpho-dynamically isomorphic to *beats*, one of four types in a broadly endorsed gesture taxonomy (along with iconics, emblems, and metaphorics, McNeill, 1992). Co-speech beats, such as emphatically hitting the air in time with vocalized utterance, serve as semantic augmentors of the spoken content itself, but they can also serve the pragmatic function of maintaining our conversational turn while we recall a word or formulate an idea. The kinesiological resemblance of some neuro-atypical stims to neurotypical individuals' routine conversational practices suggests the plausibility that stims could be interpreted and endorsed more broadly as communicative actions, paving pedagogical pathways for normalizing stimming as part of interaction within communal activities. By conceptualizing stimming as a potentially interactive resource (Chen, 2022), we hope to shift the perspectives of both the theoretical and pragmatic fields of educational psychology.

In sum, from an embodied perspective, stimming expresses and regulates the dynamics of the cognitive-affective-bodily system, influencing thinking and participating in the development of cognitive structures, elicited by the physical and cultural environment and poised to contribute to social interaction. Such a view of stimming is congruent with empirical work across the cognitive sciences. With this revised model of stimming, we turn our attention to educational practice.

Tapping the Untapped: Implications for Instructional Design

> "If 'stimming' was an acceptable and valued aspect of social and cultural behaviour, how might it be incorporated into design or social practices?" (Nolan & McBride, 2015, p. 1075)

Given our revised model of stimming, how might we adapt learning contexts to embrace and leverage stimming as part of the learning process? We recall that currently in mainstream classrooms, physical movement—be it idiosyncratic stimming or conceptual enactment—is rarely appreciated or legitimized, let alone encouraged and leveraged as cognitive activity (Montessori, 1967). Consequently, thinking by moving is suppressed into covert processes such as minute gestures or imaginary actions. We propose that inviting thinking and stimming into the classroom discourse as overt physical behaviors offer new avenues for instruction that are both more inclusive and more effective (see Feucht, 2010, on classroom *epistemic climate*). Such an invitation would occur through *instrumenting* (Vérillon & Rabardel, 1995) stimming with media that facilitate stimming activity. First, depathologizing and normalizing stimming could spare students the cognitive resources currently allocated to suppressing their need to stim and enhance stimming's impacts on arousal and mood. Further, considering *the functional superimposition of stimming and thinking* as cognitively allied processes could open new horizons for instructional design, wherein the two processes are integrated within meaningful action (i.e., *instrumentalized*, per Vérillon & Rabardel, 1995). This section will elaborate on the pedagogical conceptualization of stimming as thinking, demonstrating its potential implementation with an exploratory design for learning about mathematical functions: BBM (described in the subsequent section). We draw examples from the BBM design to propose and elaborate upon three guiding heuristics for pedagogical design: offering stim affordances ("Instrumenting Stimming" section), legitimizing stims as a discursive resource ("Interactional Stimming" section), and leveraging stims as epistemic actions ("Instrumentalizing Stimming" section).

Illustrative Empirical Context: Balance Board Math

We draw from multiple iterations and studies within a larger design-based research project, BBM, to ground and illustrate our conceptual proposal. The BBM project investigates the design conjecture that movement for learning and movement for self-regulation can be integrated to strengthen instructional efficacy. BBM focuses on the vestibular (balance) modality as an untapped resource for both regulation and learning (Tancredi et al., 2022b). BBM activities invite children to rock on large wooden balance boards to explore mathematical concepts (Fig. 2). Expressed in terms of SpEED parameters (Tancredi et al., 2022a), BBM designs novel *media*: a sensor-equipped balance board and interface facilitate and capture rocking movements, to leverages the vestibular *modality*, commonly engaged in stimming but uncommonly engaged in learning contexts, toward bringing the stim form of rocking

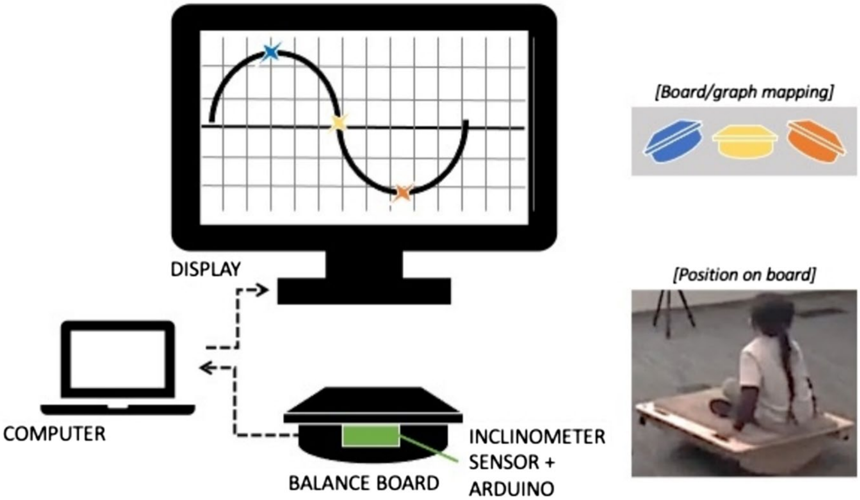

Fig. 2 Diagram of BBM graphing configuration. BBM's balance graphing activities constitute a motion-graphing learning environment controlled by the common stim of bodily rocking. Inclinometer sensors enable children seated on balance boards to generate real-time graphs of their rocking movement, projected on a screen in front of them. Graphs are generated at a steady speed, with the x-axis measuring time and the y-axis capturing the board's angular tilt moment to moment. The board may be used in a front/back configuration (as if riding a roller coaster over the graph being drawn) or a left/right configuration (as if surfing over the waves of the graph being drawn), such that rocking one direction yields an increase in y, and the other yields a decrease

into discourse as a type of gestural *semiotic mode.* In so doing, BBM draws thinking and stimming processes, typically separated and covert, together and into the open.

Working with BBM, children iteratively generate graphs within different digital environments, projected on the screen in front of them, that facilitate their discovery and control of different mathematically salient graphical properties, such as the frequency and amplitude of sinusoidal functions (Tancredi et al., 2022b). For example, in one activity, frequency exploration, each time the board rocks left and right and returns to center (one period), the screen shows how the background behind that period changes color depending on the period length (Fig. 3). Graphers also hear distinct tones each time they reach a local maximum or local minimum and each time they pass through the *x*-axis, and different chords corresponding to different colors when they complete one graphical period. Children work to understand the colors and, ultimately, to control the period (and consequently frequency) of their rocking to generate a consistent color, through rounds of graphing and reflection.

BBM is a proof-of-concept case of inclusively leveling the playing ground through creating enactive-inquiry resources that harness stims as content-oriented epistemic actions. BBM follows SpEED principles, namely (1) learning happens through the body's sensorimotor engagement with the world; (2) learning begins from learners' existing embodied resources; and (3) instruction must flexibly adapt to learners' sensorimotor diversities (Tancredi et al., 2022a). As such, BBM *leverages stimming as an embodied resource for learning*, recognizing differential stimming as an axis of diversity to be accommodated in inclusive instruction. In

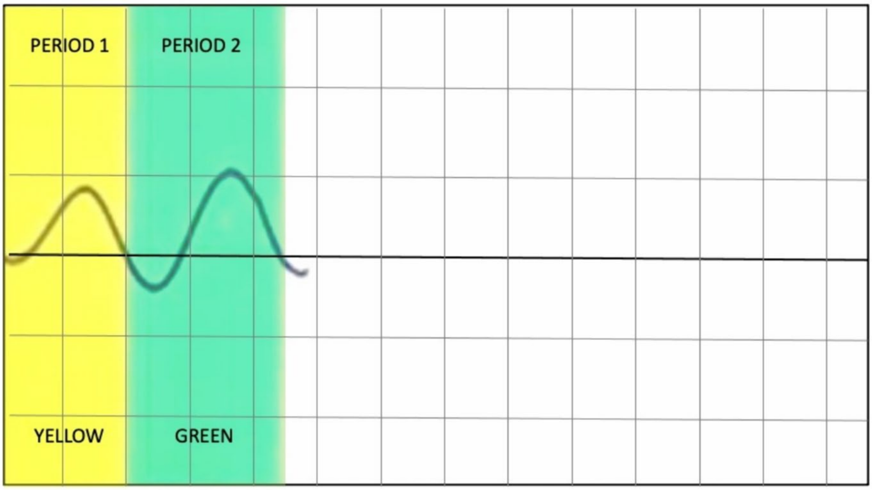

Fig. 3 Example of a graph being generated in the BBM frequency exploration activity. The focal period length here was set to 2.5 graph units. The graph is generated from left to right. First, the grapher rocked forward (in yellow, slight dip under the *x*-axis) and then backward (still in yellow, rise to a peak) before returning to balance, completing one cycle (period 1) in two time units on the *x*-axis (note the gridlines). Upon completing this period, the area behind that portion of the graph turned yellow because it was produced by rocking at a slightly higher frequency than the target frequency. Next, they rocked forward and backward once again, this time taking longer to complete the movement (just under 2.5 units on the *x*-axis) (period 2), corresponding to the focal frequency set for this round. This time, the screen turned green

outlining implications of an embodied model of stimming for pedagogical design, we share a discussion of the BBM implementation reflective of each heuristic below.

Instrumenting Stimming: Offering Stim Affordances

We propose that it is the work of pedagogy to recognize the *stim affordances* that we present to children, attending to the sensory qualities of instruction, including the type of sensory stimulation (rhythm and intensity) and the sensory systems engaged (visual, auditory, etc.). Proprioception, tactility, and balance are often the focus of stimming, so these are of particular importance here (see Tancredi, 2024). Objects, by virtue of their design, may invite or inhibit rhythmic, repetitive stim movement. Some in human–computer interaction have designed fidget widgets to offer stim affordances in the margins of computing spaces (Karlesky & Isbister, 2016). We call for such offerings to be not only in the margins but also part of the central pedagogical activity. It is also important to recognize that surrounding environments may present unpleasant, overwhelming, or impoverished stimuli. Although offering stim affordances may help make such environments more tolerable, the surrounding environment, too, must be addressed to truly offer children sensorially equitable learning experiences. This includes offering means to limit overwhelming stimuli. Instructional design must create a context of sensory comfort as a starting point, offering stim affordances as one avenue for fulfilling such sensory comfort.

BBM's physical and digital features as well as usage protocol were iteratively designed to instrumentalize stimming by offering the affordance of rocking, a common stim (Table 1). The media configuration was adapted to match the sensory stimulation to the inner ear elicited by stim rocking. For example, rather than have users stand on balance boards, wherein the head typically maintains a fixed orientation, users are invited to sit, providing rhythmic shifts in head movement. The board's base, curved in a single axis rather than multiple axes, facilitates consistent, rhythmic back-and-forth rocking movement commonly engaged for stimming. The use of a board with embedded handles and the addition of bumpers under the surface of the board allows users to safely rock to a range of angles all the way to about 45 degrees each way. Users can adjust the intensity of vestibular stimulation by self-modulating their rocking angle, ranging from slight leans left to right to sweeping rocks all the way to the board's bumpers. The BBM protocol includes a calibration procedure whereby users rock at rates and intensities comfortable to them, with graphing speed and sensor sensitivity parameters set accordingly. Thus, users can

Table 1 BBM design features offering stim affordances

BBM design feature	Stimulatory affordance
Seated board position	Vestibular-activating changes in head position
Board curved in single axis	Rhythmic back-and-forth movement
Bumpers, handles	Safe access to broad range of vestibular stimulation intensities
Calibration protocol with adjustable graphing sensitivity and speed	User-led stimulation intensity
Continuous board access	Implicit endorsement of rocking movement throughout activities and discussion

modulate the intensity of vestibular stimulation according to their sensory comfort to participate effectively. Additionally, users are welcomed to remain on the board as desired between activities during reflection and discussion, implicitly endorsing their freedom to engage in rocking movements anytime. As such, BBM offers one instantiation of how a climate of stim acceptance, found to support open stimming (Kapp et al., 2019), might be encoded into instructional materials and practices.

Interactional Stimming: Legitimizing Stims as a Discursive Resource

When welcomed in the pedagogical sphere, stimming is an overtly observable feature of interactions. Stimming's instrumentalization for thinking makes stims a prospective resource for learners and educators to make their thinking visible to peers and to communicate multimodally. Prior work has shown how designing for joint stimming is generative for inclusive, creative interaction (Chen, 2022). In the BBM project, the interactional dimension of stimming came to the fore when participants in an early iteration took turns on the board. The children spontaneously engaged in dialogue to share, refine, and test their graphing hypotheses. This led, in later BBM iterations, to the inclusion of a second balance board and collaborative activities for simultaneous and joint graphing, enabling peers to each have continuous and shared access to rocking. Thus, each child's movements are observable to their peers, and rocking is available as an ongoing interactional resource for joint reasoning. As seen in autistic play (Conn, 2015), BBM shows one way children could be invited to engage in joint stimming.

Instrumentalizing Stimming: Leveraging Stims as Epistemic Actions

An embodied view of stimming suggests that stimming is not independent of enactive thought. As such, we propose a pedagogy wherein stimming is embraced as an active part of learning itself: *stimming as thinking*. In such an approach, pedagogical activities themselves are stimmy, offering means to engage stimming not merely for regulation but as *conceptual* exploration.

The design conjecture that the stim of rocking can be instrumentalized for learning mathematical concepts has guided BBM's iterations. BBM offers children the ability to observe their rocking activity through generating a graphical trace of their activity in real time. Graphs remain observable after they are generated, allowing children to reflect on their qualities. These characteristics of BBM allow children to bring the often backgrounded process of rocking to the fore of their attention. By way of analogy, imagine a person walking on the beach, who looks back to reflect on their evenly spaced footprints in the sand—in BBM, one looks at one's graphical trace to consider mathematical properties of one's rocking. Artifacts and tools from the discipline of mathematics, such as a Cartesian grid and numbers, become, in this context, resources for refining and discussing one's rocking movements, consistent with *embodied design* principles (Abrahamson, 2014). Additionally, BBM ensures the *congruence* (Johnson-Glenberg & Megowan-Romanowicz, 2017) between stim movements and focal concepts. For example, children explore the concept of amplitude as the degree of tilt in either direction of flat (0), frequency as their rate of rocking, and slope as the slope of the board's surface. Rocking movements are not merely a stimulating input device, but rather a multimodal experience of both the focal concept and the mathematical representation of that concept (i.e., the slope of the graph line). In this context, learners can modulate the amplitude and timing of their rocking to develop new movement patterns as the basis for emerging graphing concepts, just as the infants in Thelen et al.'s studies (1993) modulated their stereotyped arm movements in amplitude and timing to become refined, effective movement patterns.

We put forth BBM as an example of design where stims become available as an interactional resource, dynamically enfolded into not only children's thinking, but also their communication, supporting the coordination of joint action and preceding, illustrating, or complementing the ideas they express verbally. We propose that, when instrumentalized, stimming can play a functional role in facilitating children learning to move in new ways that bear import for mathematical thinking.

Conclusion and Implications

A 4E analysis of the historically marginalized activity of stimming yields precepts for a new model of stimming as (a) reflective and regulatory of the cognitive system, (b) influential upon thinking, (c) forming a substrate for complex actions and concepts, (d) responsive to properties of the physical and cultural environment, and (e) socially communicative. Stimming offers an essential means to organize coherent sensorimotor experience. Stimming actions, articulated across time, space, and people, can structure the flow of internal and external sensory inputs and harmonious interaction with the environment. We have highlighted preliminary empirical substantiation for this view across multiple fields of cognitive science.

This theoretical analysis reveals stimming to be an interactional resource with not only social but also epistemic potential when endorsed as such. It is but an artifact of cultural-historical factors that this form is presently unrealized. When we center the cognitive needs of neurodivergent learners in instructional design, we stand to enrich learning opportunities for everyone. We distill the implications of this perspective into the following set of tentative pedagogical design heuristics for inclusive learning environments:

(1) *Instrument* stimming: offer stim affordances. This entails designing environments and tools with an eye toward their stimulatory possibilities: the opportunities that they present to tap, bounce, spin, and move, ideally catering to a range of possibilities to accommodate the diversity of user's sensory profiles. For example, the BBM balance boards enable children to rock at different intensities, self-differentiating for their own sensory needs.

(2) *Interactional* stimming: legitimize stims as a discursive resource. This entails attending to learner's stims in learning contexts with the assumption that these stims are part of nonverbal communication and can serve as a window into the dynamics of a learner's thought, as well as affective experience. For example, children in BBM can rock in ways that make visible their engagement with others' ideas.
(3) *Instrumentalize* stimming: leverage stims as epistemic actions.[7] This entails teaching in such a way that children's stims can be made relevant to the concepts being taught: for example, using rocking angle to teach slope. By providing children with means to document, modulate, and reflect on their stims, they can become means to explore pedagogical concepts. For example, in BBM, children can generate graphs of their rocking stims, enabling them to ultimately use rocking as a way to reflect on graphing concepts such as frequency and amplitude.

We have offered axiological, theoretical, and empirical arguments for depathologizing stimming across special and general education. Therefore, we challenge prevalent perceptions of stimming as nonessential, involuntary, and task-irrelevant. Instead, we theorize stimming as maintaining the dynamic equilibrium of the cognitive–affective system and, when enabled, capable of intrinsically driving problem solving and social interaction. Further exploration and design evaluation is warranted to actualize stim-inclusive educational practice.

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Declarations

Ethics Approval and Consent to Participate This article does not include human subjects data. The "position on the board" image in Fig. 2 is from a study approved by the ethics committee of San Francisco State University and University of California, Berkeley. The procedures used in that study adhere to the tenets of the Declaration of Helsinki. Informed consent, including regarding publishing their data and photographs, was obtained from legal guardians and assent was obtained from all BBM participants.

Conflict of Interest The authors declare no competing interests.

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[7] We do not argue that *all* stimming should be instrumentalized. Stimming plays multiple and dynamic roles in people's lives and wellbeing. To constrain all stimming to serve academic learning would itself be a restrictive practice.

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