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Interactional Gestural Synchrony as a Mechanism of Embodied Learning: A Theoretical Account

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Abstract

This article develops a theoretical account of how interactional gestural synchrony may support embodied learning. Research on embodied cognition suggests that conceptual understanding is partly grounded in sensorimotor simulation, while research on gesture shows that bodily action can support communication, reasoning, and memory. However, most accounts of embodied learning treat gesture primarily as an individual cognitive resource or as an instructional aid produced by the teacher. The present article proposes that synchronized teacher-student gesture may constitute a distinct interpersonal mechanism of embodied learning. We argue that gestural synchrony can align three concurrent processes: the learner's internal sensorimotor simulation, the learner's overt gestural enactment, and the teacher's overt gestural modelling. This temporal alignment may facilitate learning by strengthening shared attention, stabilizing sensorimotor representations, reducing ambiguity in concept-gesture mapping, and supporting the consolidation of embodied memory traces. The article distinguishes gestural synchrony from related constructs such as mimicry, behavioral matching, alignment, and collaborative gesture, and identifies testable predictions for future research. The proposed account suggests that embodied learning should be understood not only as an individual sensorimotor process, but also as an interactionally coordinated process that emerges through temporally structured bodily communication between teachers and learners.

Significance Statement

Gesture is a common feature of instruction, yet educational research has often examined teacher gesture and learner gesture separately. This article proposes that the timing relation between teacher and learner gestures may itself be cognitively consequential. The central claim is that interactional gestural synchrony may align a learner's internal sensorimotor simulation with the learner's own gesture and the teacher's gesture. This alignment may strengthen learning by increasing shared attention, stabilizing concept-gesture mappings, and supporting memory for concepts that have spatial, dynamic, or action-related structure. The article has practical relevance for classroom instruction, teacher education, multimodal pedagogy, and the design of embodied learning activities. It also provides a basis for empirical work using video coding, motion tracking, eye tracking, retention tests, and classroom observation to determine when synchrony facilitates learning and when it does not. The account therefore connects a real-world instructional issue, how bodily coordination between teachers and learners shapes learning, with basic questions about simulation, attention, memory, and conceptual representation.

1. Introduction

Embodied approaches to cognition propose that thinking and learning are shaped by perception, action, and bodily engagement with the world, rather than by abstract symbol manipulation alone (Barsalou, 2010; Gallagher, 2023). In educational research, this view has motivated increasing attention to gesture, action, object manipulation, virtual environments, and movement-based learning. Evidence from

mathematics, science, and language learning indicates that bodily activity can support conceptual understanding, especially when the activity is meaningfully related to the structure of the concept being learned (Alibali & Nathan, 2012; Johnson-Glenberg & Megowan-Romanowicz, 2017; Macedonia, 2019; Novack et al., 2014).

Gesture has a central role in this literature because it links bodily action with communication. Teachers use gesture to represent spatial relations, dynamic processes, quantities, procedures, and abstract relations. Learners use gesture to express emerging ideas, reduce processing demands, and construct representations that may not yet be fully verbalized (Goldin-Meadow, 2003; Hostetter & Alibali, 2008, 2019). Gesture is therefore not only a visible supplement to speech, but also a possible component of conceptual processing. However, most accounts of gesture in embodied learning have focused on gesture as an individual cognitive resource or as an instructional aid produced by the teacher. Less attention has been given to the possibility that temporally coordinated gestures between teacher and learner may constitute a distinct interpersonal mechanism of embodied learning.

The present article addresses this issue by developing a theoretical account of interactional gestural synchrony in learning. We define interactional gestural synchrony as the temporal coordination of gesture production between two or more interactants during a shared instructional episode. Synchrony may involve similar gesture forms, but exact form matching is not required. Its defining feature is temporal alignment in relation to shared conceptual content. For example, a teacher and a learner may both trace an upward movement while discussing a rising graph, or a learner may point to a diagram at the same moment that the teacher traces a relevant spatial relation. In both cases, the relevant phenomenon is not merely that gesture occurs, but that gestures are temporally organized around the same representational task.

Interactional synchrony has been examined across several areas of social and cognitive research, including psychotherapy, linguistics, psychology, education, and movement science (e.g., Fitzpatrick et al., 2016; Nozawa et al., 2016; Ramseyer & Tschacher, 2011). It refers to the dynamic coordination of behavior between individuals during interaction, particularly in contexts involving shared communicative or goal-directed activity. Related constructs include alignment (Garrod & Anderson, 1987; Garrod & Pickering, 2004), mimicry (Cheung et al., 2015; Lakin et al., 2008), interpersonal coordination (Bernieri et al., 1988), and behavioral matching (Bernieri & Rosenthal, 1991; Louwerse et al., 2012; Cornejo et al., 2017). Although these constructs differ in emphasis, they converge on the idea that social interaction is often structured by temporal and behavioral coordination. Bernieri and Rosenthal (1991, p. 403) defined interactional synchrony as “the degree to which the behaviors in an interaction are non-random, patterned or synchronized in both timing and form,” thereby emphasizing both temporal alignment and behavioral organization.

Empirical research suggests that interactional synchrony is functionally relevant across several domains. In clinical settings, synchrony between therapist and patient has been associated with therapeutic alliance and treatment-related outcomes (Ramseyer & Tschacher, 2011). In motor and performance

contexts, synchrony has been examined in dance, sport, and coordinated action (Araújo et al., 2016; Passos & Chow, 2016; Torrents et al., 2016; Yamamoto et al., 2016). Research has also linked synchrony to social bonding, affiliation, trust, prosocial behavior, communicative coordination, and prediction during interaction (Hoehl et al., 2021; Zampella et al., 2020). These findings suggest that synchrony is not merely a by-product of interaction, but a structured process that can influence social, communicative, and performance-related outcomes. However, its possible role in conceptual learning and knowledge acquisition remains less fully specified.

This gap is important because learning in classrooms and instructional interactions is rarely an individual process alone. Learners often acquire knowledge through temporally organized exchanges with teachers, peers, tools, representations, and bodily actions. From an embodied cognition perspective, these interactions may shape the sensorimotor simulations through which concepts are understood and remembered. The distinction between know-how and know-that is relevant here (Ryle, 1949). Know-how refers to procedural and skill-based knowledge acquired through embodied engagement, whereas know-that refers to propositional or fact-based knowledge. Although these forms of knowledge are often treated separately, embodied cognition suggests that even propositional knowledge may be partly grounded in sensorimotor experience. Mathematical rules, conceptual relations, spatial transformations, and scientific processes may be learned not only through verbal explanation, but also through bodily and perceptual engagement with representations.

Building on this view, the central proposal of the present article is that interactional gestural synchrony may support embodied learning by coordinating three representational processes within a narrow temporal window: the learner's internal sensorimotor simulation, the learner's overt gestural enactment, and the teacher's overt gesture. This triadic alignment may provide convergent internal and external cues that stabilize the learner's representation of the target concept. The proposed account does not assume that synchrony is always beneficial. Rather, it specifies conditions under which synchrony should support learning, including gesture relevance, concept type, timing, prior knowledge, and cognitive load.

The contribution of this article is theoretical. It aims to extend embodied learning research from an individual to an interactional level of analysis. Specifically, it argues that gesture should not be understood only as a learner-generated or teacher-generated resource, but also as a temporally coordinated interpersonal process. To develop this argument, the article first reviews relevant work on embodied learning and gesture. It then distinguishes interactional gestural synchrony from related constructs such as mimicry, alignment, behavioral matching, and collaborative gesture. Next, it presents a triadic alignment model of gestural synchrony in embodied learning, identifies candidate mechanisms, discusses boundary conditions, and derives testable predictions for future research.

2. Embodied learning

In the past two decades, a growing body of empirical evidence has supported the effectiveness of embodied learning in facilitating the acquisition of new knowledge across a wide range of domains,

including mathematics (e.g., Alibali & Nathan, 2012; Martinez-Lincoln et al., 2018), foreign language learning (e.g., Macedonia, 2019), language processing (Khatin-Zadeh et al., 2023), science education (e.g., Johnson-Glenberg & Megowan-Romanowicz, 2017; Lindgren et al., 2016; Stieff et al., 2016), and engineering education (e.g., Alibali et al., 2011). Collectively, these studies suggest that learning is not solely a symbolic or abstract cognitive process, but is significantly shaped and enhanced by bodily engagement with the environment. In general, theories of embodied learning emphasize the central role of the body, bodily actions, and interaction with concrete objects in the construction and development of knowledge (Khatin-Zadeh et al., 2022). From this perspective, cognition is deeply grounded in sensorimotor experience, such that perception and action are not merely supportive mechanisms but constitutive components of learning itself. Fuchs (2016), for example, argues that embodied knowledge is acquired through both habitual and volitional actions, which establish stable and recurring connections between the body and the physical environment. These connections are continuously shaped by prior experiences, allowing learners to build meaning through recurrent patterns of interaction (Fuchs, 2016).

Embodied learning theories propose that when learning processes are supported by concrete environmental artifacts, bodily movements, and sensorimotor engagement, the effectiveness of learning is significantly enhanced (Khatin-Zadeh et al., 2025). Within this framework, embodiment enables the activation and coordination of sensorimotor networks that ground abstract or symbolic knowledge in concrete experiential contexts (Khatin-Zadeh et al., 2022). Through repeated interaction with the environment, these grounded experiences contribute to the formation of embodied memory traces, which support long-term knowledge retention and retrieval (Ianì, 2019). In practical educational settings, embodied learning approaches have been operationalized through a variety of instructional tools and techniques designed to integrate bodily experience into the learning process. These include the use of gesture-based instruction, manipulation of concrete physical objects, play-based learning activities, computer-assisted learning environments, and immersive technologies such as virtual reality. Across these implementations, the underlying assumption is that grounding abstract concepts in sensorimotor experience provides a more robust and accessible pathway for knowledge development, thereby bridging the gap between symbolic reasoning and embodied experience.

3. Gesture studies

Among the various strands of research within embodied education, gesture studies occupy a particularly prominent position. Gestures can be considered one of the most accessible and cost-effective tools in embodied pedagogy, as they can be readily implemented in virtually any classroom setting, including those with limited access to technological or material resources. Their pedagogical value lies in the fact that they naturally integrate bodily movement with communicative intent, thereby linking conceptual content with sensorimotor experience in a direct and intuitive manner. Three interrelated properties—being visual, dynamic, and inherently interactive—make gestures especially powerful as scaffolding tools for learning processes. First, gestures are inherently visual and flexible, which allows them to be adapted to a wide range of conceptual domains and instructional contexts. Because of this flexibility, they can be

used to externalize abstract ideas and transform them into visually grounded representations that are more accessible to learners. In this way, gestures can function as a bridge between symbolic descriptions and perceptual experience, facilitating comprehension when learners are required to engage with spatial or visual representations of concepts (Khatin-Zadeh et al., 2025). Second, many domains in mathematics, science, and engineering are deeply structured around motion-based metaphors and dynamic processes. In mathematics, for instance, concepts such as vectors, limits, and continuity are frequently described in terms of movement or change over time. In physics, core constructs such as force and acceleration are explicitly defined through dynamic interactions, while in engineering, systems are often conceptualized as evolving or moving entities. These examples reflect a broader tendency in scientific reasoning to rely on motion-based conceptualizations. In such contexts, gestures provide a natural medium for enacting these dynamic relations physically, thereby supporting learners in developing an embodied understanding of otherwise abstract or formalized ideas (Khatin-Zadeh et al., 2025). Third, gestures are interactive, and this interactivity becomes particularly important in classroom environments where learning is socially distributed.

In recent years, research has increasingly demonstrated the positive role of collaborative gesture production in enhancing learning outcomes across different domains (Walkington et al., 2019). Collaborative gestures are those intentionally produced by two or more individuals working jointly toward a shared instructional or problem-solving goal. This distinguishes them from gestural synchrony, which refers to spontaneous and often automatic temporal coordination of gestures that emerges during interaction. Importantly, while collaborative gestures are goal-directed and may differ in timing, form, or structure between participants, gestural synchrony is characterized by temporal and often structural alignment in gesture production. This distinction is theoretically significant, as collaborative gestures and gestural synchrony may serve different cognitive and communicative functions within learning contexts. Whereas collaborative gestures primarily support joint task construction and explicit coordination of problem-solving strategies, gestural synchrony may operate more implicitly, facilitating interpersonal alignment, shared attention, and the implicit structuring of interactional flow. Given these differences, it is necessary to treat them as distinct but potentially complementary mechanisms within embodied learning environments. Here, we focus specifically on gestural synchrony and its potential role in knowledge development. In the following section, we elaborate on the proposal that temporal synchronization of gestures may play a facilitative role in the acquisition of embodied knowledge by shaping cognitive alignment and enhancing the integration of perceptual, motor, and conceptual processes during learning.

4. Interactional gestural synchrony

According to theories of embodiment, when an individual uses a linguistic expression to refer to a concrete object or mentally represents that object, the same sensorimotor systems that are engaged during actual perception and interaction with that object are reactivated (e.g., Barsalou, 2010; Feldman & Narayanan, 2004; Pulvermüller, 2005, 2013). Importantly, this reactivation does not require the physical presence of the object in the immediate environment; rather, it can occur entirely through internal

cognitive processes. For instance, when a student mentally processes the geometric concept of a pyramid, sensorimotor networks associated with perceiving its shape, spatial structure, and orientation may be recruited even in the absence of an actual pyramid. In this sense, the learner is not merely retrieving an abstract definition, but is engaging in a form of perceptual simulation grounded in prior embodied experience. This internally generated simulation can be understood as a fully mental process that operates independently of direct environmental input, yet remains grounded in the body's previous interactions with the world. Such a process is often discussed in the literature as a form of weak embodiment (Gallagher, 2023). Here, we further specify this mechanism by referring to it as *internal embodiment*, emphasizing that the relevant simulation occurs entirely within the cognitive system without requiring a physically observable realization in the external environment. The term *internal* is used here to highlight that the embodied simulation is instantiated at the level of neural and mental processes rather than through overt bodily action.

Within the broader framework of 4E cognition, cognition is not conceived as a purely internal and detached computational process, but as fundamentally embodied, embedded, enacted, and, in some formulations, extended (Carney, 2020; Durt et al., 2017; Gallagher, 2023; Newen et al., 2018). From this perspective, bodily processes—particularly gesture—are not peripheral accompaniments to cognition but integral components of cognitive activity itself. Building on this view, Hostetter and Alibali (2008, 2019) propose that when a mental simulation reaches a certain level of activation or "threshold", it may be externalized in the form of gesture. This transition from internal simulation to overt bodily expression has also been discussed in relation to extended or distributed accounts of cognition (Gallagher, 2018; Kiverstein, 2018). In line with this literature, we refer to this outward realization of internal simulation as *external embodiment*. The term *external* emphasizes that the mental simulation is no longer confined to internal cognitive processes but becomes instantiated in the physical, observable environment through bodily action. External embodiment can be manifested in the gestures produced by the learner themselves or in those produced by an interaction partner, such as a teacher, who co-constructs meaning through bodily expression. In the case of interactional gestural synchrony, external embodiment is distributed across both participants, such that teacher and student jointly produce temporally coordinated gestures that instantiate related aspects of the same conceptual simulation. This distributed externalization is a key feature of interactional gestural synchrony and may play a crucial role in supporting knowledge development. In such contexts, the gestures produced by the interaction partner (e.g., the teacher) function as an external scaffolding mechanism that supports, shapes, and stabilizes the learner's ongoing internal simulations. In other words, the interactor's gestures provide a perceptible model that can guide the learner's own processes of mental simulation and potential gestural realization, thereby facilitating the alignment between internal embodiment and external embodiment during the learning process.

Interpersonal gestural synchrony creates a particularly rich context for knowledge development because it provides multiple, mutually reinforcing resources for the embodiment and acquisition of conceptual understanding across different domains. In such settings, mental embodiment in the student's mind is not an isolated process, but is continuously supported and shaped by both the student's own gestural

activity and the gestural activity of the interactor (e.g., the teacher). In other words, gestural synchrony brings together multiple modes of representing and enacting the same conceptual content within a single coordinated interactional episode. More specifically, three partially distinct but tightly interconnected forms of embodiment can be identified. The first is *internal embodiment*, which consists of the student's fully mental simulation of the concept, grounded in sensorimotor memory and prior experience. The second and third are forms of *external embodiment*, realized through overt gesture: one generated by the student and the other generated by the interactor. Importantly, these three processes do not occur in isolation or sequence, but co-occur in real time within the interactional context, forming a temporally aligned and dynamically integrated system of embodied simulation. This simultaneity is theoretically significant because it creates a densely layered multimodal environment in which the same conceptual content is instantiated across internal and external representational systems. As a result, the embodied representation of the concept becomes more robust, redundant, and mutually reinforcing. The student is not relying solely on internal simulation, nor solely on externally observed gesture, but on a continuously interacting system in which internal and external embodiments resonate with one another during learning. On this basis, it can be assumed that synchronized gestural embodiment leaves a stronger imprint on embodied memory systems compared to non-synchronized or unidirectional forms of embodiment. The simultaneous presence of multiple embodied cues may increase the salience, stability, and retrievability of the learned material by repeatedly activating overlapping sensorimotor networks within a short temporal window. In this sense, internal embodiment is continuously scaffolded by two externally observable gestural streams—the student's own gestures and those of the interactor—which together provide a richer and more structured input for cognitive processing. Overall, this multimodal and temporally synchronized configuration offers an enriched representational environment that supports the integration of perception, action, and conceptual understanding. By aligning internal simulation with externally observable embodied actions, interpersonal gestural synchrony may therefore enhance both the encoding and consolidation of embodied knowledge within memory systems.

5. Candidate Mechanisms

5.1 Shared attention

One mechanism through which gestural synchrony may support learning is shared attention. Gesture can guide attention to relevant spatial locations, features, or relations. When teacher and learner gestures are temporally coordinated, the learner's attention may be directed toward the same representational element at the same moment in the instructional explanation. This temporal concentration may reduce ambiguity about which part of the representation is currently relevant. Shared attention is especially important in domains where learners must coordinate multiple representations, such as a diagram, a verbal explanation, and a mathematical notation. If a teacher points to a graph while describing change over time and the learner simultaneously traces the same trajectory, the timing relation may help bind the spoken term, visual feature, and bodily movement into a single event

representation. The learning benefit should therefore depend on whether synchrony aligns attention with task-relevant information.

5.2 Stabilization of sensorimotor simulation

A second mechanism is the stabilization of sensorimotor simulation. Internal simulations can be incomplete, unstable, or poorly matched to the target concept, especially for novice learners. Teacher gesture may provide an external sensorimotor scaffold that helps learners select relevant dimensions of the concept. Learner gesture may then enact the selected dimensions. Synchrony may be beneficial because the external scaffold and the learner's own action converge while the simulation is being constructed. This mechanism predicts that synchrony should be most useful when learners are developing a new sensorimotor-conceptual mapping. It should be less useful when learners already possess a stable representation, or when the concept lacks a meaningful spatial or action-related structure. It should also be less useful when the synchronized gesture is irrelevant or misleading.

5.3 Reduction of representational ambiguity

Many instructional gestures are underdetermined. A pointing gesture may refer to a location, an object, a relation, or a step in a procedure. A sweeping gesture may indicate direction, continuity, increase, or movement. Temporal coordination between teacher and learner gestures may reduce this ambiguity by allowing both participants to align gesture, speech, and task context around a shared referent. In this sense, synchrony can function as a constraint on interpretation. This mechanism is related to alignment in dialogue, but it is more specifically embodied. The relevant alignment is not only between linguistic representations, but also between bodily enactments and conceptual structures. If both teacher and learner enact the same relation at the same moment, the learner may be more likely to identify the intended mapping between movement and concept.

5.4 Encoding and retrieval support

A fourth mechanism concerns memory. Gesture can support durable learning, as shown by evidence that producing gestures during instruction can improve later retention (Cook et al., 2008). The triadic alignment model predicts that synchronized gesture may strengthen memory because it creates a richer encoding episode. The learner encodes the concept through verbal information, internal simulation, self-produced movement, and observed teacher movement within a shared temporal window. This claim should be treated as a hypothesis rather than an established conclusion. The strongest version of the hypothesis is that synchrony produces benefits beyond those produced by teacher gesture alone, learner gesture alone, or non-synchronized co-occurring gestures. To test this claim, future studies must include comparison conditions that equate the amount and semantic relevance of gesture while varying timing.

6. Boundary Conditions

The proposed account does not imply that all synchrony improves learning. Several boundary conditions are necessary.

First, gesture relevance is critical. Synchrony should support learning only when the gestures represent task-relevant conceptual content. Synchronized but irrelevant gestures may add extraneous processing demands and could impair learning. Second, the type of concept should matter. The benefit should be stronger for spatial, dynamic, procedural, and action-related concepts than for content with weak sensorimotor structure. Third, prior knowledge should moderate the effect. Learners with very low prior knowledge may not understand the gesture-concept mapping, while learners with high prior knowledge may not need the additional scaffold. Fourth, timing precision should matter. Some degree of temporal overlap may be useful, but exact simultaneity may not always be required. In some cases, slight lag may be beneficial if the learner follows the teacher's model after observing it. Fifth, cognitive load should be considered. Synchrony may facilitate integration when it highlights relevant information, but it may increase load when learners must monitor complex bodily coordination in addition to difficult content.

These boundary conditions are important because they prevent the account from treating synchrony as a universally beneficial instructional technique. They also make the model falsifiable. If synchronized but irrelevant gestures improve learning as much as semantically relevant synchrony, the proposed mechanism would need revision. If synchrony helps equally across concept types, the sensorimotor grounding component would be weakened. If timing has no effect after gesture amount and gesture relevance are controlled, the synchrony-specific claim would not be supported.

7. Testable Predictions

The model generates several empirical predictions. First, learners exposed to semantically relevant synchronized teacher-student gestures should show better immediate comprehension and delayed retention than learners exposed to equivalent gestures that are temporally misaligned. Second, this advantage should be stronger for concepts with clear spatial, dynamic, or action-based structure than for concepts that are primarily arbitrary or verbally defined. Third, the effect of synchrony should be mediated by shared attention and by the quality of gesture-concept mapping. Fourth, synchrony should be more beneficial when learner gesture is active rather than merely observed, because self-produced movement contributes to encoding. Fifth, excessive, irrelevant, or poorly timed synchrony should not improve learning and may reduce performance by increasing extraneous cognitive load.

Several methodological approaches could test these predictions. Laboratory studies can manipulate the timing of teacher and learner gestures while holding gesture content constant. Classroom studies can code naturally occurring teacher-student gestural synchrony and relate it to learning outcomes. Motion tracking can quantify timing, amplitude, and phase relations. Eye tracking can examine whether synchrony increases shared attention to relevant visual information. Delayed tests can determine whether synchrony affects memory consolidation rather than only immediate comprehension.

A useful experimental design would compare four conditions: teacher gesture only, learner gesture only, synchronized teacher-learner gesture, and non-synchronized teacher-learner gesture. The synchronized and non-synchronized conditions should contain the same gesture forms and verbal explanations,

differing only in timing. This design would allow researchers to test whether temporal coordination adds explanatory value beyond the presence of gesture itself.

8. Implications for Instruction

The practical implication of the model is not that teachers should ask learners to imitate every instructional gesture. Instead, teachers may benefit from designing moments in which gesture, speech, visual representation, and learner action are coordinated around key conceptual relations. For example, in mathematics instruction, teacher and learner gestures may be synchronized when representing slope, rotation, equivalence, or transformation. In science instruction, synchrony may be useful when representing forces, fields, cycles, flows, or molecular motion. In language learning, synchronized enactment may support action verbs, spatial prepositions, or constructions with imageable meaning.

Instructional use of synchrony should remain selective. The teacher should identify concepts for which movement clarifies structure. The gesture should be simple enough that learners can coordinate it without losing attention to the concept. Learners should also have time to verbalize or otherwise reflect on the mapping between gesture and concept, because bodily coordination alone may not guarantee conceptual understanding. In this sense, gestural synchrony is best treated as one component of multimodal instruction, not as a substitute for explanation, feedback, and practice.

9. Limitations of the Account

The present article offers a theoretical account and should not be read as evidence that gestural synchrony has already been shown to produce robust learning gains across educational domains. Direct evidence is still needed. Much of the current rationale is derived from adjacent findings on gesture, embodied learning, interpersonal synchrony, and memory. These literatures justify the hypothesis, but they do not establish the specific causal pathway proposed here.

A second limitation concerns measurement. Gestural synchrony is not a unitary variable. It can differ in timing precision, gesture form, semantic congruence, amplitude, frequency, and relation to speech. Future work must specify which features of synchrony are being measured and why they should matter cognitively. A third limitation concerns ecological validity. Highly controlled laboratory studies may isolate timing effects, but classroom interaction is more complex. Naturalistic studies are needed to determine whether synchrony emerges spontaneously in instruction and whether it predicts learning after controlling for teacher quality, student engagement, prior knowledge, and task difficulty.

10. Conclusion

Interactional gestural synchrony may provide an important but underexamined mechanism in embodied learning. By temporally coordinating the learner's internal simulation, the learner's gesture, and the teacher's gesture, synchrony may create conditions in which conceptual information is encoded through convergent sensorimotor, attentional, and social cues. This account extends embodied learning theory

by emphasizing that embodiment in education is not only individual, but also interactional. The account also clarifies what must be tested. Future studies should determine whether gestural synchrony produces learning benefits beyond teacher gesture, learner gesture, and collaborative gesture alone. They should examine whether benefits depend on gesture relevance, concept type, timing, prior knowledge, and cognitive load. If supported, the model would provide a basis for understanding how bodily coordination between teachers and learners contributes to conceptual learning and memory. If not supported, the findings would still clarify the limits of embodied and interactional accounts of learning.

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The authors declare that they have no conflict of interest.

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References

1. Alibali MW, Nathan MJ (2012) Embodiment in mathematics teaching and learning: Evidence from learners' and teachers' gestures. J Learn Sci 21(2):247–286. https://doi.org/10.1080/10508406.2011.611446
2. Alibali MW, Spencer RC, Knox L, Kita S (2011) Spontaneous gestures influence strategy choices in problem solving. Psychol Sci 22(9):1138–1144. https://doi.org/10.1177/0956797611417722
3. Araújo D, Ramos JP, Lopes RJ (2016) Shared affordances guide interpersonal synergies in sport teams. In: Chow JY (ed) Interpersonal coordination and performance in social systems. Routledge, pp 165–178
4. Barsalou LW (2010) Grounded cognition: Past, present, and future. Top Cogn Sci 2(4):716–724. https://doi.org/10.1111/j.1756-8765.2010.01115.x
5. Bernieri FJ, Reznick JS, Rosenthal R (1988) Synchrony, pseudosynchrony, and dissynchrony: Measuring the entrainment process in mother–infant interactions. J Personal Soc Psychol 54(2):243–253. https://doi.org/10.1037/0022-3514.54.2.243
6. Bernieri FJ, Rosenthal R (1991) Interpersonal coordination: Behavioral matching and interactional synchrony. In: Feldman RS, Rimé B (eds) Fundamentals of nonverbal behavior. Cambridge University Press, pp 401–432
7. Carney J (2020) Thinking avant la lettre: A review of 4E cognition. Evolutionary Stud Imaginative Cult 4(1):77–90. https://doi.org/10.26613/esic/4.1.172
8. Cheung EO, Slotter EB, Gardner WL (2015) Are you feeling what I'm feeling? The role of facial mimicry in facilitating reconnection following social exclusion. Motivation Emot 39(4):613–630. https://doi.org/10.1007/s11031-015-9479-9
9. Cornejo C, Cuadros Z, Morales R, Paredes J (2017) Interpersonal coordination: Methods, achievements, and challenges. Front Psychol 8., Article 1685. https://doi.org/10.3389/fp
10. Del-Monte J, Capdevielle D, Varlet M, Marin L, Schmidt RC, Salesse RN et al (2013) Social motor coordination in unaffected relatives of schizophrenia patients: A potential intermediate phenotype. Front Behav Neurosci 7:137. https://doi.org/10.3389/fnbeh.2013.00137
11. Durt C, Fuchs T, Tewes C (2017) Embodiment, enaction, and culture: Investigating the constitution of the shared world. MIT Press
12. Feldman J, Narayanan S (2004) Embodied meaning in a neural theory of language. Brain Lang 89(2):385–392. https://doi.org/10.1016/S0093-934X(03)00355-9

13. Fitzpatrick P, Frazier JA, Cochran DM, Mitchell T, Coleman C, Schmidt RC (2016) Impairments of social motor synchrony evident in autism spectrum disorder. Front Psychol 7:1323. https://doi.org/10.3389/fpsyg.2016.01323
14. Fuchs T (2016) Embodied knowledge–embodied memory. In S. Rinofner-Kreidl & H. Wiltsche (Eds.), *Analytic and continental philosophy: Methods and perspectives. Proceedings of the 37th International Wittgenstein Symposium* (pp. 215–229). De Gruyter. https://doi.org/10.1515/9783110450651-015
15. Gallagher S (2018) The extended mind: State of the question. South J Philos 56:421–447. https://doi.org/10.1111/sjp.12309
16. Gallagher S (2023) Embodied and enactive approaches to cognition. Cambridge University Press
17. Garrod S, Anderson A (1987) Saying what you mean in dialogue: A study in conceptual and semantic co-ordination. Cognition 27(2):181–218. https://doi.org/10.1016/0010-0277(87)90018-7
18. Garrod S, Pickering MJ (2004) Why is conversation so easy? Trends Cogn Sci 8(1):8–11. https://doi.org/10.1016/j.tics.2003.10.016
19. Hoehl S, Fairhurst M, Schirmer A (2021) Interactional synchrony: Signals, mechanisms and benefits. Soc Cognit Affect Neurosci 16(1–2):5–18. https://doi.org/10.1093/scan/nsaa024
20. Hostetter AB, Alibali MW (2008) Visible embodiment: Gestures as simulated action. Psychon Bull Rev 15(3):495–514. https://doi.org/10.3758/PBR.15.3.495
21. Hostetter AB, Alibali MW (2019) Gesture as simulated action: Revisiting the framework. Psychon Bull Rev 26(3):721–752. https://doi.org/10.3758/s13423-018-1548-0
22. Ianì F (2019) Embodied memories: Reviewing the role of the body in memory processes. Psychon Bull Rev 26(6):1747–1766. https://doi.org/10.3758/s13423-019-01674-x
23. Johnson-Glenberg MC, Megowan-Romanowicz C (2017) Embodied science and mixed reality: How gesture and motion capture affect physics education. Cogn Research: Principles Implications 2., Article 24. https://doi.org/10.1186
24. Khatin-Zadeh O, Banaruee H, Farsani D (2025) The role of executive functions in symbolic and situational mathematical abilities. Eur J Psychol Educ 40., Article 1. https://doi.org/10.1007/s10212-024-00903-9
25. Khatin-Zadeh O, Farsani D, Eskandari Z, Marmolejo-Ramos F (2022) The roles of motion, gesture, and embodied action in the processing of mathematical concepts. Front Psychol 13:969341. https://doi.org/10.3389/fpsyg.2022.969341
26. Khatin-Zadeh O, Hu J, Eskandari Z, Yanjiao Z, Farsani D, Banaruee H (2023) Gestural simulation of motion verbs. Am J Psychol 136(4):349–366. https://doi.org/10.5406/19398298.136.4.03
27. Kiverstein J (2018) Extended cognition. In: De Bruin NL, Gallagher S (eds) The Oxford handbook of 4E cognition. Oxford University Press, pp 19–40
28. Lakin JL, Chartrand TL, Arkin RM (2008) I am too just like you: Nonconscious mimicry as an automatic behavioral response to social exclusion. Psychol Sci 19(8):816–822. https://doi.org/10.1111/j.1467-9280.2008.02162.x

29. Lindgren R, Tscholl M, Wang S, Johnson E (2016) Enhancing learning and engagement through embodied interaction within a mixed reality simulation. Comput Educ 95:174–187. https://doi.org/10.1016/j.compedu.2016.01.001
30. Macedonia M (2019) Embodied learning: Why at school the mind needs the body. *Frontiers in Psychology*, *10*, Article 2098. https://doi.org/10.3389/fpsyg.2019.02098
31. Martinez-Lincoln A, Tran LE, Powell SR (2018) What the hands tell us about mathematical learning. Gesture 17(3):375–416. https://doi.org/10.1075/ge
32. Newen A, De Bruin L, Gallagher S (2018) The Oxford handbook of 4E cognition. Oxford University Press
33. Nozawa T, Sasaki Y, Sakaki K, Yokoyama R, Kawashima R (2016) Interpersonal frontopolar neural synchronization in group communication: An exploration toward fNIRS hyperscanning of natural interactions. NeuroImage 133:484–497. https://doi.org/10.1016/j.neuroimage.2016.03.059
34. Passos P, Chow JY (2016) Interpersonal coordination in team sports. In J. Y. Chow (Ed.), *Interpersonal coordination and performance in social systems* (pp. 154–164)
35. Pulvermüller F (2005) Brain mechanisms linking language and action. Nat Rev Neurosci 6(7):576–582. https://doi.org/10.1038/nrn1706
36. Pulvermüller F (2013) How neurons make meaning: Brain mechanisms for embodied and abstract-symbolic semantics. Trends Cogn Sci 17(9):458–470. https://doi.org/10.1016/j.tics.2013.06.004
37. Ramseyer F, Tschacher W (2011) Nonverbal synchrony in psychotherapy: Coordinated body movement reflects relationship quality and outcome. J Consult Clin Psychol 79(3):284–295. https://doi.org/10.1037/a0023419
38. Ryle G (1949) *The concept of mind*. Hutchinson
39. Stieff M, Lira ME, Scopelitis SA (2016) Gesture supports spatial thinking in STEM. Cognition Instruction 34(2):80–99. https://doi.org/10.1080/07370008.2016.1145122
40. Torrents C, Hristovski R, Coteron J, Ric Á (2016) Interpersonal coordination in contact improvisation dance. In: Chow JY (ed) Interpersonal coordination and performance in social systems. Routledge, pp 94–108
41. Walkington C, Chelule G, Woods D, Nathan MJ (2019) Collaborative gesture as a case of extended mathematical cognition. J Math Behav 55:100683. https://doi.org/10.1016/j.jmathb.2
42. Yamamoto Y, Okumura M, Yokoyama K, Kijima A (2016) Interpersonal coordination in competitive sports contexts: Martial arts. In: Chow JY (ed) Interpersonal coordination and performance in social systems. Routledge, pp 179–194
43. Zampella CJ, Csumitta KD, Simon E, Bennetto L (2020) Interactional synchrony and its association with social and communication ability in children with and without autism spectrum disorder. J Autism Dev Disord 50:3195–3206. https://doi.org/10.1007/s10803-020-04412-8