From Action Imitation to Predictive Processing: Dynamic Neural Mechanisms and Practical Application Prospects of Motor Contagion

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Abstract

Motor contagion, as a core mechanism of dynamic coupling between perceptual and motor systems in human social interaction, has long been a subject of debate regarding its neural mechanisms and evolutionary significance. In social interactions, the unconscious influence on an individual' s own actions triggered by observing others' actions is referred to as motor contagion. Motor contagion constitutes the foundation of human imitation and social learning, playing a crucial role in social cognition, group coordination, and other aspects. Research suggests that the essence of motor contagion lies in the dynamic interaction among the perceptual system, motor system, and social-cognitive network. The mirror neuron system plays a fundamental role in shared representations for action observation and execution, but its function must be understood within the overarching framework of prediction error regulation and conscious pathway competition. Predictive processing theory, through feedforward models that calibrate internal action representations, reveals the regulatory role of prediction errors on the directional plasticity of motor contagion, elucidating the behavioral diversity ranging from imitation to deviation. Social context modulates contagion intensity via the prefrontal cortex, indicating that motor contagion possesses adaptively significant functions endowed by evolution. Future research should integrate psychology, neuroscience, and computational modeling through interdisciplinary synthesis to deepen the analysis of dynamic interaction mechanisms and explore practical applications in complex social scenarios.

Full Text

From Action Imitation to Predictive Processing: The Dynamic Neural Mechanism and Practical Application Prospects of Motor Contagion

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Abstract

Motor contagion, as a core mechanism for the dynamic coupling of perception and action systems in human social interaction, has long been subject to controversy regarding its neural mechanisms and evolutionary significance. In social communication, the unconscious influence on one' s own actions triggered by observing others' actions is termed motor contagion. It forms the foundation of human imitation and social learning, playing a critical role in social cognition, group coordination, and other domains. Research suggests that the essence of motor contagion lies in the dynamic interaction among the perceptual system, motor system, and social cognitive networks. While the mirror neuron system serves as a foundational role in the shared representation of action observation and execution, its function must be understood within the broader framework of predictive error regulation and competition between conscious pathways. The predictive processing theory calibrates internal action representations through forward models, revealing how predictive errors modulate the directional plasticity of motor contagion and explaining the behavioral diversity from imitation to deviation. Social contexts regulate the intensity of contagion via the prefrontal cortex, indicating that motor contagion possesses adaptive functions endowed by evolution. Future research should integrate interdisciplinary approaches from psychology, neuroscience, and computational modeling to deepen the analysis of dynamic interaction mechanisms and explore practical implementations in complex social scenarios.

Keywords: motor contagion, neural mechanisms, mirror neuron system, predictive processing, social cognition

As a social species, human survival and reproduction have always depended on group cooperation. In this process, individuals transmit information not only through language but also through non-verbal action synchronization to achieve intention understanding. From infants unconsciously imitating their parents' facial expressions [?] to the spontaneous convergence of applause rhythms in audiences [?], and to the unconscious jumping of all team members during soccer corner kicks [?], this phenomenon of synchronization across time and space is essentially the concrete expression of "motor contagion" —the unconscious influence on one's own actions triggered by observing others' actions [?, ?].

Motor contagion not only constitutes the foundation of human imitation and social learning but also plays a critical role in social cognition and group coordination. From early observations of spontaneous imitation behaviors to modern experimental analyses of neural mechanisms, the research history of motor contagion has revealed the profound coupling between perception and action, providing key clues for understanding the embodiment of social cognition. The neural mechanisms and evolutionary significance behind this phenomenon remain highly controversial: Is the essence of motor contagion based on "hard-coded" imitation through the mirror neuron system, or is it adaptive behavior dynamically regulated by predictive processing? Exploring these questions not only concerns the analysis of the "social brain" essence [?] but also has profound implications for applications in sports training and neurological rehabilitation.

Over the past three decades, motor contagion research has undergone a theoretical leap from single neural mechanisms to multi-system integration. Researchers have gradually revealed the neurophysiological mechanisms and dynamic regulatory processes underlying motor contagion through behavioral experiments, neuroimaging, and computational modeling [?]. Within this theoretical framework, there exists a highly overlapping neural circuit between observation and execution, which not only supports direct action imitation but may also enable prediction, evaluation, and adjustment of motor output in complex social contexts. The early breakthrough originated from the discovery of the "mirror neuron system": Rizzolatti and colleagues observed in the ventral premotor cortex (area F5) and inferior parietal lobule (area PFG) of macaques that the same group of neurons were activated both when the individual performed grasping actions and when observing similar actions performed by conspecifics, revealing a direct "observation-execution" matching mechanism [?]. Subsequent neuroimaging studies further confirmed that human mirror neuron system-related brain regions also become active during observation-execution processes [?]. However, a single mirror mechanism struggles to explain dynamic adjustments in complex social interactions. In recent years, with the development of computational neuroscience and dynamic systems theory, researchers have begun to re-examine motor contagion from computational and ecological perspectives. A series of new studies have explored the implicit information processing and feedback mechanisms during the transmission of body movements and facial expressions in social contexts [?]. These studies focus not only on static imitation phenomena but also emphasize the importance of information integration and prediction in dynamic environments, giving rise to the emergence of "multilevel network theory," which posits that motor contagion may be initiated by low-level mirror systems providing motor resonance signals, while high-level predictive networks endow behavioral flexibility through error regulation [?]. This "from imitation to prediction" process demonstrates that motor contagion is not merely simple copying of external movements but rather a dynamically regulated behavior based on internal prediction and feedback mechanisms. During this process, observers not only receive external action information but also integrate their own past motor experiences and expected goals through internal representations to generate predictions about future motor outcomes. Recent research has found that the cerebellum' s function extends beyond sensorimotor control, as it predicts outcomes of motor and cognitive tasks through "forward models" and adjusts behavior by comparing predicted and actual outcomes [?, ?, ?]. Striatal dopamine modulates behavior through the antagonistic actions of D1 and D2 receptors [?]. These findings further expand theoretical boundaries, offering new perspectives for understanding predictive errors and feedback regulation in motor contagion.

Despite significant progress in existing research, most motor contagion studies have focused on behavioral and mechanistic explanations while neglecting the regulatory role of social cognition. Therefore, this article aims to review previous research on motor contagion, 梳理 the theoretical evolution and neural mechanisms of motor contagion, and 展望 its interdisciplinary application prospects. By integrating multidisciplinary achievements from psychology, neuroscience, and computational modeling, we attempt to construct a hierarchical dynamic framework to reveal the continuum nature of motor contagion from low-level imitation to high-level prediction. This endeavor not only helps deepen our understanding of human action comprehension mechanisms but also provides scientific evidence for optimizing motor training strategies, designing neurorehabilitation interventions, and developing adaptive human-machine systems.

2 The Evolution of Theoretical Frameworks: From Imitation to Prediction

The research history of motor contagion represents a cognitive evolution from natural phenomenon observation to experimental scientific analysis. Early researchers gradually constructed frameworks ranging from theoretical interpretation to behavioral description through keen observation of spontaneous imitation phenomena, while innovations in experimental paradigms continuously drove theoretical breakthroughs.

2.1 The Automaticity of Imitation: Perception-Action Shared Representation

The theoretical construction of motor contagion revolves around the proposition of the "perception-action cycle," with its core lying in how action observation influences action execution. Different cognitive theories emphasize the close relationship between perception and action. Ecological theory provides the philosophical foundation for environmental interaction [?, ?]. Gibson' s [?] concept of "affordances" emphasizes that the perception of environmental stimuli is essentially the recognition of embodied action possibilities. When observers identify action possibilities in the environment, this perception directly activates corresponding motor representations. This direct coupling relationship between environment and actor provides an important theoretical framework for understanding how action observation transforms into action execution. Psychological research further deepens this discovery at the cognitive level through common-coding theory, which posits that action perception and action execution share the same representational system [?]. Brass et al. [?] conducted an experiment using a simple reaction-time task where participants were required to execute preset finger movements based on finger movements displayed on a screen. In the experiment, the observed finger movements were either compatible with the movements to be executed (e.g., observing a "tapping" action while needing to execute a "tapping" action) or incompatible (e.g., observing a "lifting" action while needing to execute a "tapping" action). The results showed that reaction times were significantly reduced when observed movements were compatible with executed movements, and significantly increased when they were incompatible.

These experimental results confirm the shared representation mechanism of the perception-action system. When observing an action, the motor system in the brain automatically activates the corresponding motor representation. If the observed action matches the prepared action, it facilitates execution; if inconsistent, it interferes with execution. Common-coding theory provides a robust theoretical foundation for understanding the complex relationship between observed and executed actions. In this process, imitation does not depend on action intention but rather on the similarity between observed actions and planned actions, a phenomenon also known as "automatic imitation" [?].

Automatic imitation is a form of motor contagion that refers to the unconscious imitation of observed actions [?]. To verify the unconscious nature of automatic imitation, one study examined it through a "matching pennies" game. The experiment required one participant to win when gestures matched and the other to win when they mismatched. Participants were alternately blindfolded to test whether they would unconsciously imitate opponents' gestures despite incentives to avoid imitation. By analyzing the imitation frequency of sighted participants under different incentive conditions, researchers found that participants still showed imitation tendencies even when incentivized to avoid imitation [?]. These results demonstrate that this imitative behavior is largely independent of individual intention and conscious control, proving the "automaticity" of automatic imitation.

Although automatic imitation possesses automaticity, it is not entirely independent of individual awareness and control [?]. When participants were not informed about biomechanical differences between actions, they showed similar automatic imitation effects for both possible and impossible actions, indicating that actions were primarily encoded at the goal level while ignoring specific movement patterns. However, when participants were explicitly informed that they would see possible and impossible actions, automatic imitation only occurred for biomechanically possible actions, not for impossible ones [?]. This suggests that when attention is directed to the specific manner of action, action encoding shifts from the goal level to the movement pattern level, thereby affecting automatic imitation. Additionally, social attitudes have been found to influence automatic imitation directly and specifically. Researchers explored the imitation of specific actions primed by prosocial or antisocial attitude words and found that participants primed with prosocial words showed stronger imitation behavior than those primed with antisocial words. This imitation was unconscious and occurred even when it contradicted task intentions, suggesting that imitation can occur beyond intentional control [?]. These findings reveal that the automaticity of automatic imitation is regulated not only by attentional input but also by social cognitive factors, demonstrating that automatic imitation is not entirely stimulus-driven but is influenced by top-down cognitive control and task settings.

Heyes [?] introduced dual-route models to explain this phenomenon. The automatic route can directly activate corresponding responses without conscious control or intention when facing stimuli. When observing an action, the automatic route may unconsciously activate a response topographically similar to the observed action, even if this action is irrelevant to the current task. In other words, the automatic route cannot be directly altered by conscious processes and is automatically driven by task-irrelevant stimuli. The conscious route, however, selects and executes responses based on current task requirements and goal-directed thinking. If the task requires individuals to execute a response that mismatches the observed action, the conscious route will be activated to execute the correct task-related response, which can explain task-related actions. That is, when observers see others performing an action, the unconscious route may automatically activate motor representations corresponding to the observed action, producing imitative behavior that is automatic and does not require conscious decision-making. However, when observers need to execute tasks inconsistent with observed actions, conflict arises between conscious and unconscious routes, potentially causing interference or errors during task execution. Through automatic imitation, observers can unconsciously imitate others' actions in their brains, a process that may facilitate action understanding. Therefore, automatic imitation is considered a potentially important mechanism for understanding others' actions.

2.2 The Priority of Intention: Hierarchical Action Understanding

How do we understand others' actions? As a core capacity of social cognition, action understanding has two main hypotheses explaining how the brain achieves it: the "visual hypothesis" and the "direct matching hypothesis." These hypotheses reveal the complex operating mechanisms of human action understanding systems from different dimensions.

The visual hypothesis is rooted in traditional cognitive psychology paradigms,

主张 that the visual system specifically decodes biological motion features, believing that the brain can complete intention inference by analyzing spatiotemporal features of actions (such as point-light motion trajectories) without motor system involvement [?, ?]. This hypothesis provides a visual information processing perspective for understanding actions, but its limitation of over-reliance on visual modality gradually becomes apparent. Research shows that congenitally blind individuals can acquire action representations through non-visual pathways, and these representations can support effective interaction with others without visual experience [?], indicating that while the visual system can independently decode low-level motion features, it cannot explain non-visual modality representations or high-level intention inference. The direct matching hypothesis, however, posits that observers achieve "embodied understanding" by directly mapping the visual representation of observed actions onto corresponding motor representations in their own brains [?, ?].

A series of studies provided key evidence. Researchers first demonstrated that goal-directed actions are unconsciously influenced by distractors: when targets to be grasped appeared simultaneously with distractors of different sizes, the peak amplitude of grip aperture increased with distractor size. The results showed that distractors produced unconscious interference effects on goal-directed action execution. Subsequently, researchers further explored whether this interference effect could be transmitted between individuals through observation: participants were divided into observers and executors, with executors performing grasping actions under specific conditions while observers later attempted to replicate these actions. By manipulating the presence of distractors, the executor' s gaze direction, and the visibility of body parts, the study investigated how these factors influenced observers' perception and execution of actions. The results showed that interference effects transferred from executors to observers, who were unconsciously influenced by the executor's action features and gaze direction even without actual action execution [?, ?]. These findings reveal that when imitating observed actions, observers prioritize imitation of goals or intentions rather than kinematic details. Even when distractors affect the executor' s actions, observers still infer action intentions through gaze direction, and this inference is unconscious. The results support the direct matching hypothesis, demonstrating that observers can automatically activate the motor system through intention inference even without direct action demonstration. This goal- or intention-oriented imitation is also a form of motor contagion. When imitating an observed goal-directed action, individuals tend to imitate the goal rather than the action kinematics, revealing that people prioritize imitating higher-level goal components over lower-level movement components.

These findings confirm the hierarchical processing characteristics of action understanding: when high-level intentions are clear, the influence of low-level kinematic features diminishes. The mirror system is responsible for processing embodied action imitation, directly decoding low-level kinematic features by matching observed actions with one' s own motor experience. The mentalizing system, however, is responsible for high-level intention inference, reasoning about abstract goals or mental states through integration with social cognitive networks [?]. Motor contagion can be explained through hierarchical processing models, where imitation is triggered by extracting high-order goal representations, consistent with "top-down" intention-driven processing in hierarchical models: the visual system provides initial action features, while intention inference requires motor system participation in embodied simulation, with both achieving functional coupling through hierarchical models. Therefore, motor contagion may also be the first step toward mentalizing.

2.3 The Regulatory Nature of Prediction: Error-Driven and Model Calibration

Some have proposed that motor contagion may be the first step in predicting others' actions, and this contagion process may provide a starting point for understanding others' actions [?, ?]. A new paradigm examined the behavioral interaction between action production and outcome prediction. Researchers asked dart experts to observe novice dart throws and predict the throwing outcomes, receiving feedback on correct results after prediction. The results showed that dart experts' own throwing performance gradually deteriorated after watching novice throws, while their outcome prediction ability significantly improved. When feedback on prediction results was removed, experts' outcome prediction ability did not improve, and their own throwing performance did not deteriorate [?]. This indicates that improved outcome prediction ability is the cause of deteriorated motor performance. Predictive processing theory provides a new computational perspective for explaining these results. This theory posits that the brain explains external world perceptual inputs by generating internal predictive models. These models, based on past experience and knowledge, help individuals predict upcoming events. When predictions align with actual perceptual inputs, brain processing efficiency is higher; when they mismatch, predictive errors are generated, and the brain adjusts internal models to reduce these errors [?, ?].

In other words, when experts predict others' action outcomes, the adjustment of their brain' s internal models not only affects their predictive accuracy for others' actions but also influences their own action control. This adjustment represents an adaptive change made by the brain to better understand and predict others' actions, but it inadvertently affects the expert' s perception and control of their own actions. Under the unification of predictive processing theory, motor contagion breaks through the traditional imitation theoretical framework. In the prediction process, there must be a "cognitive starting point" to estimate the target we are observing. We believe that motor contagion is precisely the key mechanism providing this starting point [?]. Motor contagion brings observers "closer" to executors, significantly reducing initial prediction uncertainty and providing a high-precision starting point for prediction cycles.

To further reveal hierarchical effects of prediction precision, researchers conducted an experiment requiring hammer throw athletes to throw toward the center of a field after watching videos of a model throwing hammers left, center, and right. The videos showed two types of movement kinematics: one difficult to predict throwing direction, and another easy to predict. The results showed that athletes' throws deviated toward their predicted throwing direction of the model, and this deviation was only observed after watching the easily predictable videos [?]. Although participants' movement kinematics did not match the observed action changes, their throwing direction was still unconsciously influenced by what they observed. This indicates that motor contagion depends more on predicting action outcomes than on imitating specific action kinematics. Therefore, when actions are easier to predict, they more readily activate observers' internal predictive models, thereby enhancing motor contagion. This activation promotes the brain' s prediction of action outcomes while strengthening motor system activation, reducing cognitive load and improving understanding of action intentions. The combined effect of these factors makes observers more susceptible to motor contagion.

To further investigate whether prediction errors affect human motor behavior, researchers conducted a baseball pitching experiment. Baseball players were randomly divided into three groups: no prediction error group, prediction error group, and control group. An alternating pitching and observation task design was employed. Participants in the no prediction error and prediction error groups wore opaque glasses during pitching, preventing them from seeing where the ball hit the target. During observation tasks, they watched videos of a pitcher and reported where the ball hit the target. Prediction errors were manipulated through different instructions: the no prediction error group was told that the pitcher' s target location varied to reduce prediction errors, while the prediction error group was told the pitcher always aimed at the center, thereby inducing prediction errors. The control group only performed pitching tasks without observation tasks. The results showed that when observation was accompanied by prediction errors, baseball players exhibited patterns different from traditional motor contagion—their actions did not become similar to observed actions but gradually deviated from them, and this process was unconscious [?]. This indicates that prediction errors play a crucial role, not only changing the direction of motor contagion but also revealing the dual influence of observation and prediction on motor behavior.

This prediction error-induced motor contagion represents a novel form of contagion, similar to the process of adjusting actions through error correction in motor learning, which aligns with the core tenets of predictive processing theory —that the brain adjusts internal models to correct prediction errors. Therefore, motor contagion is not merely simple imitation but is regulated by predictive processing mechanisms. Predictive processing theory can explain why observers' actions sometimes resemble observed actions and sometimes deviate, with these differences likely depending on the magnitude and direction of prediction errors.

Based on these findings, Ikegami et al. [?] added the concept of a predictive system to the original dual-route model, attempting to integrate and explain the automatically activated motor representations in individuals when observing others' actions and how these representations are modified by prediction errors. First, observers perceive others' actions through the visual system, and this perceptual information is input to the brain' s motor and perceptual regions. During task execution, observers receive instructions or requirements, which can be external or internal. The brain uses observed actions and task instructions to predict upcoming action features, generating predictions based on past experience and current context. When actual observed action features mismatch predictions from the predictive system, prediction errors arise. This mismatch can be based on differences in action kinematics, outcomes, or goals. Subsequently, prediction errors trigger adjustments to the predictive system, potentially involving modification of motor representations in the brain. This modification aims to reduce future prediction errors and improve predictive accuracy. Prediction error-driven motor representation modification leads to prediction error-induced contagion in observers' actions, which may manifest as actions dissimilar to observed action features or even opposite actions. The modified motor representations ultimately influence observers' action execution, including adjusting action planning, execution, and feedback loops. At this point, observers can identify and adjust their actions through self-monitoring to reduce the impact of prediction error-induced contagion, potentially involving conscious changes to action plans or execution strategies. Through practice and feedback, observers can further adjust and optimize their action representations and execution strategies, thereby improving action accuracy and efficiency. Thus, this model also provides a unified theoretical framework for studying action imitation, motor contagion, and motor learning.

3 Hierarchical Integration of Neural Mechanisms: Mirror, Resonance, and Predictive Systems

Theoretical models require support from neuroscientific evidence. The essence of motor contagion lies in the dynamic coupling between observers' motor systems and external stimuli. The theoretical framework for this phenomenon has evolved from single neural representation models to predictive processing models. Motor contagion originated from early discoveries of the mirror neuron system but has gradually transcended single physiological mechanism interpretations, developing into a key clue for understanding "embodied cognition" in complex social interactions.

3.1 The Mirror System: Neural Matching Foundation for Observation-Execution

The discovery of mirror neurons represents a landmark breakthrough in cognitive neuroscience. Initially discovered in the ventral premotor cortex (area F5) and inferior parietal lobule (area PFG) of macaques, these neurons discharge both when the monkey performs specific hand actions and when observing similar actions performed by conspecifics or humans [**?**]. This "observation-execution" dual-mode characteristic reveals the embodied mechanism of action understanding, laying the cornerstone for subsequent human mirror neuron system research.

The existence of the human mirror neuron system has been confirmed through multimodal evidence. Neurophysiological studies found that when individuals observe others' actions, their motor cortex becomes active even without overt motor activity, indicating that the human motor system possesses mirror properties [?, ?, ?, ?]. Brain imaging studies revealed that observing others' actions activates a complex network including occipital, temporal, and parietal visual areas, as well as two major motor-related regions: the inferior parietal lobule and inferior frontal gyrus, which constitute the core of the human mirror neuron system [?, ?, ?, ?, ?, ?]. When observing others' actions, corresponding motor representations are automatically activated, leading observers' motor systems to tendentially replicate features of observed actions, forming motor contagion.

Furthermore, research found that macaque mirror neurons are insensitive to visual features of actions, responding only to goal-directed actions of biological agents. However, in humans, non-goal-directed actions or simple movement observation can also activate the motor system, which may form the basis of human imitation ability [?]. These findings negate the visual hypothesis based on visual information processing, forming a system that matches action observation and execution, supporting the role of the motor system in action imitation and understanding, and laying a neural mechanism foundation for subsequent research.

Classic functional magnetic resonance imaging experiments revealed the neural computational mechanisms of imitation. Researchers used fMRI to measure brain activity during observation and imitation of finger movements and when executing the same movements based on spatial or symbolic cues. The experiment set up three observation conditions and three observation-execution conditions, contrasting simple finger movements under imitation and non-imitation conditions. The study found that the left inferior frontal gyrus and right superior parietal lobule were activated during finger movements regardless of how they were triggered, with higher activation when the same movements were triggered by observing others perform identical movements [?]. This indicates that the left inferior frontal gyrus and right superior parietal lobule in the brain are responsible for describing observed actions and encoding precise kinematic details of movements, respectively. This dual-stream processing mechanism perfectly 诠释了 the direct matching hypothesis, with the inferior frontal gyrus transforming visual input into motor goal representations and the superior parietal lobule implementing visuomotor transformation of motor parameters. These findings provide direct experimental evidence for the neural mechanisms of human imitation.

3.2 Motor Resonance: From Intrapersonal to Interpersonal Neural Synchronization

Motor resonance, as the core functional mechanism of the mirror neuron system, has expanded from a simple neural mirroring phenomenon to a multi-level regulated social cognitive framework. This mechanism posits that motor resonance maps the visual representation of observed actions onto observers' own motor representations to achieve action understanding [?].

Rizzolatti et al. [?] pioneeringly divided motor resonance into explicit and implicit dual modes: explicit motor resonance manifests as - cross-frequency coupling in premotor and primary motor cortices, triggering unconscious imitation behavior; implicit motor resonance is reflected in enhanced functional connectivity between Broca' s area and temporoparietal junction, responsible for action intention decoding. When individuals observe others performing actions, the brain generates neural activity related to those actions, but this activity does not directly trigger explicit unconscious imitation behavior. Both types of motor resonance are based on motor system activation during action observation. The basic mechanism of explicit motor resonance is direct activation of the motor system, primarily involving premotor and primary motor cortices. Implicit motor resonance, while not producing overt motor responses, forms motor copies of observed actions in the brain that help understand others' action intentions, primarily involving higher-order premotor cortex areas. Mirror neurons function in implicit motor resonance, with their activity related to action understanding rather than mere imitation. This classification focuses on the neurophysiological mechanisms of motor resonance and its role in imitation and action understanding. Moreover, motor resonance may also play an important role in interpersonal interactions.

At the neural oscillation level, Uithol et al. [?] proposed a two-dimensional model of motor resonance that further divides it into "intrapersonal resonance" and "interpersonal resonance." Intrapersonal resonance refers to resonance between observers' visual and motor systems, manifested as phase coupling between visual-motor -band power decrease and motor cortex -band event-related desynchronization, with its intensity modulated by motor experience. When individuals observe actions, representations first form in the visual system and are then transmitted to the motor system. If matching motor representations exist in the motor system for observed actions, resonance occurs. Interpersonal resonance refers to functional correspondence between observers' motor systems and actors' motor systems. This resonance emphasizes "shared representation" between observers and actors. For example, in dyadic coordination tasks, -band neural synchrony in the right parietal region significantly increases, particularly when participants exhibit action synchrony [?]. In this case, observers' motor system activation occurs because of similarity with actors' motor representations rather than direct mapping from visual to motor representations, and this neural synchrony may reflect regulatory mechanisms in social interaction.

These findings support the central role of the motor system in action understanding, revealing the connection between the mirror neuron system and action observation-execution. Traditional views hold that motor resonance is a bottom-up automatic process dependent on low-level motor feature matching [?]. One study found that social interaction significantly enhances motor resonance (assessed through transcranial magnetic stimulation-evoked motor potentials), and participants who exhibited imitation behavior during social interaction showed stronger motor resonance when subsequently observing actions [?]. This indicates that social interaction can enhance human brain motor resonance for observed human behavior, and this enhancement is achieved by modulating the mirror neuron system, with imitation behavior potentially amplifying this regulatory effect. In other words, motor resonance does not occur automatically but is subject to top-down regulation, influenced not only by external stimuli but also by observers' internal factors.

Motor resonance, as the core mechanism of motor contagion, lays the foundation for understanding its neural mechanisms. This process extends beyond action imitation to involve deeper intention inference and social interaction, providing important neuroscientific evidence for explaining how humans understand others' actions and intentions through observation.

3.3 The Predictive Framework: Forward Models and Error Minimization

In sports, elite athletes must not only execute complex actions but also predict other athletes' behaviors, a capability crucial for performance that enables them to gain advantages in rapidly changing competitive scenarios. Researchers found through transcranial magnetic stimulation experiments that elite basketball players showed significantly higher corticospinal excitability (manifested as motor-evoked potential amplitude) when observing basketball actions compared to observing soccer actions or static images, and could effectively distinguish successful from unsuccessful shooting actions through hand kinematic features, demonstrating professional-specific action prediction. Expert observers showed similar basketball-action-sensitive patterns but lacked neural representations for predicting action outcomes. Novices could only distinguish dynamic from static stimuli and could not specifically identify differences in movement types [?]. This indicates that elite athletes show increased premotor cortex activation when observing basketball free throws, particularly when predicting erroneous actions. This ability may be closely related to their motor experience, implying that long-term motor training can modulate the brain's motor resonance system to automatically predict others' action outcomes through observation, revealing the central role of motor contagion mechanisms in competitive performance.

Schubotz' s [?] predictive forward model provides a theoretical framework for these findings and explores how humans use the motor system to predict external events. Traditionally, the motor system was considered primarily responsible for pre-encoding motor commands and interference-free execution, but this model emphasizes the importance of internal forward models (predictors) that simulate the dynamics of the body and environment, capturing causal relationships between actions and their outcomes. Through a series of functional magnetic resonance imaging studies, researchers found that predicting abstract events activates premotor cortex and its parietal projection areas, with activation patterns showing preferences across modalities (auditory and visual) but without specialization. Even for events we cannot reproduce, we can effectively use the sensorimotor system for imitation. This imitation is based on sensorimotor representations that do not transform into actual actions because they lack proprioceptive and other interoceptive information, which is the essential difference between event prediction and motor imagery. When observers cannot execute observed actions, they can still establish sensorimotor representations as forward models. Event prediction can be viewed as a Bayesian strategy that optimizes expectations through weighted combinations of priors and sensory likelihoods. Prediction errors are treated as perceptual errors in early learning stages and as real changes in the external world in advanced learning stages [**?**]. This framework breaks the traditional assumption that "the motor system only serves action control," revealing its fundamental role in broader cognitive functions. Simultaneously, it provides a unique perspective for understanding motor contagion: when observed objects are executable human actions, predictive mechanisms manifest as unconscious imitation; when objects are non-executable natural events, they manifest as expectation generation based on partial sensorimotor representations. This perspective not only unifies neural mechanisms for action and non-action prediction but also provides a more general framework for understanding motor contagion.

Notably, this contagion mechanism based on non-action cues may explain the long-standing baseball tradition that batters' performance is influenced by previous batters' performance—if previous batters successfully hit the ball, the current batter' s success rate also increases [**?**]. Traditional explanations for this belief attribute it to psychological factors such as morale boosting. However, recent evidence suggests that motor contagion may play a key role, with batters experiencing motor contagion triggered by observing the kinematic features of previous batters' swing actions. But this cannot explain why substitute players in the "bullpen" who did not directly observe batting actions were still affected. To investigate whether contagion could be triggered by physical motion laws or symbolic systems without human action observation, researchers examined batters' performance after observing three types of non-action stimuli: motion trajectories, outcome locations, and symbolic information. The results showed that batting direction was unconsciously influenced, with the greatest effect from motion trajectories, followed by outcome locations, and no significant effect from symbolic information. Experienced batters were sensitive to both motion trajectories and outcome locations, showing stronger response intensity and longer duration; less experienced batters showed only weak effects from motion trajectories [**?**]. This indicates that baseball batters' performance can be influenced by motor contagion triggered by non-action physical cues, with intensity closely related to experience. Experienced batters can not only directly activate motor prediction programs through ball trajectory dynamics but also reverse-engineer potential motion laws from static outcome locations, forming multi-level forward models; novices rely only on explicit motion cues, reflecting the predictive system' s dependence on prior knowledge. This finding provides an explanation for why substitute players who did not observe swing actions were still affected: high-level athletes can reverse-activate action patterns stored in premotor cortex by observing ball trajectories or outcomes, achieving "outcome-action" inverse simulation.

The study further validated Schubotz' s theoretical framework that the human motor system establishes abstract predictive models through embodied simulation mechanisms without requiring actual action execution or human action observation. The ineffectiveness of symbolic information reveals the modality-specific nature of the predictive system, which fundamentally relies on physical dynamics representations rather than abstract symbols. The generation and processing of prediction errors are core mechanisms driving the plasticity of motor contagion behavior. Neuroscientific evidence indicates that the cerebellum plays a pivotal role in this process [?, ?]. The cerebellum receives signals from cortical motor areas (such as premotor and parietal cortices) via mossy fibers and compares them in real-time with actual sensory feedback received through climbing fibers. If differences exist, prediction error signals are generated, which may influence behavior through two pathways: one is upward modulation, where error signals are transmitted to the cortex (such as motor and prefrontal cortices) to modify predictive models and action plans; the other is internal model updating, which drives adaptive adjustments of internal motor representations in the cerebellum to minimize future errors [?]. Therefore, in motor contagion, when observers' predictions mismatch actual observed outcomes, the cerebellum detects significant prediction errors, and its output correction signals directly cause subsequent actions to deviate from observed movement patterns rather than simple imitation.

In summary, the cerebellum may be a crucial component in implementing the "prediction-error-correction" cycle, where internal models (stored in cerebello-cortical circuits) serve as carriers for action imitation, and prediction errors (computed by the cerebellum) are the driving force for model updating and behavioral adaptation. These findings not only extend motor contagion mechanisms from traditional action imitation to physical law prediction but also provide new insights for motor training—by strengthening perceptual training of kinematic cues, athletes' predictive representational abilities may be optimized, thereby enhancing decision-making efficiency in complex motor situations.

4 Practical Applications: Social Context-Driven Contagion Regulation

As a core cognitive mechanism connecting perception and action, motor contagion' s theoretical evolution and neural mechanism analysis provide profound scientific support for interdisciplinary practice. From perception-action shared representation to dynamic regulation of internal models, motor contagion research has transcended phenomenological description to delve into the hierarchical structure of neural circuits and computational mechanisms. These findings not only reveal the underlying logic of human action imitation and understanding but also endow it with broad practical potential. Based on this, we elaborate on application pathways in sports, neurorehabilitation, and human-machine collaboration from three perspectives, revealing the scientific landscape of theory-to-practice transformation.

4.1 Competitive Optimization: Skill Acquisition and Strategic Contagion

In skill learning, motor contagion demonstrates unique advantages distinct from observational learning. Through automatic mapping of the mirror neuron system and dynamic calibration of prediction errors, athletes achieve efficient internalization of action representations. Compared to observational learning requiring conscious participation, motor contagion directly transforms visual input into motor commands through resonance in ventral premotor cortex and inferior parietal lobule, effectively reducing cognitive load [**?**].

During this process, multiple brain regions coordinate their activity. The superior temporal sulcus and middle temporal gyrus participate in extracting kinematic parameters of actions and project this information to premotor cortex through the dorsal visual stream to generate motor commands, achieving visuomotor mapping [**?**]. This process provides fundamental integration of visual and motor information for action execution. The cerebellum dynamically adjusts motor representations through prediction error signals, optimizing action learning processes and forming error correction circuits [**?**], thereby enhancing skill learning efficiency.

The practical value of motor contagion is manifested in its adaptability to complex situations. The mirror neuron system can synchronously integrate multiple cues such as proprioception, audition, and vision to form multimodal action representations, maintaining action fluency under high-pressure situations and significantly outperforming consciousness-dominated strategies [**?**]. Based on these mechanisms, motor training paradigms have been innovated. Implicit demonstration design intersperses unconventional action demonstrations during training to induce prediction errors and enhance plasticity of premotor-primary motor cortex circuits. This mechanism of prediction and correction is particularly crucial in team sports requiring high-level coordination, as it enables individual behavior to become more adaptive and coordinated through continuously updated internal models. Additionally, neurofeedback training can help participants learn to regulate brain rhythms and improve complex motor skill levels by real-time monitoring and modulation of -rhythm power [**?**].

Compared to traditional learning methods, motor contagion shows significant advantages in neural pathways, temporal efficiency, and situational adaptability. Its reliance on automatic mapping mechanisms of the mirror neuron system avoids resource consumption from prefrontal conscious control and hippocampal explicit memory encoding, reducing cognitive load while achieving dynamic error calibration through cerebello-basal ganglia circuits. Future research could further strengthen contagion effects through targeted modulation of ventral premotor cortex excitability or utilize digital twins of virtual athletes to transmit elite athletes' neural patterns in real-time, breaking through traditional training spatiotemporal limitations.

Notably, the role of motor contagion is not only reflected in process optimization of skill acquisition but also holds critical value in upgrading prediction and response systems in competitive sports scenarios. Research shows that high-level basketball players exhibit increased premotor cortex activation when observing free throws and can extract information from action kinematics earlier for prediction, whereas novices lack this selective activation [?]. This reveals a "neural pre-activation" phenomenon that enables faster responses to stimulus signals, improving reaction speed and efficiency, but also implies that high-level athletes possess stronger motor contagion capacity.

When athletes can accurately predict opponents' action outcomes, contagion effects are enhanced, but athletes' action patterns do not necessarily simply imitate opponents; instead, they may exhibit more complex strategic adjustments. The purpose of competitive sports is "competition" rather than "cooperation," where motor contagion reflects not only the intensity of motor resonance but also observers' meta-cognitive evaluation of action sources. One study primed adult participants with prosocial or non-social vocabulary, observing reversed contagion directions: contagion effects enhanced under prosocial conditions but diminished under non-social conditions [?]. This indicates that social contexts can modulate the intensity of motor contagion. Functional magnetic resonance imaging studies further found that both cooperative and competitive contexts activated prefrontal and parietal cortices, indicating that both social interactions require monitoring self and others' behaviors. However, these contexts differ significantly in neural mechanisms. Cooperative contexts specifically activated the left medial orbital frontal cortex, a region related to reward processing and positive feedback, reflecting that cooperation may be a social reward process. Competitive contexts, however, activated the right parietal cortex and medial prefrontal cortex, regions related to self-other distinction and mentalizing abilities, indicating that competition requires more self-other distinction and mentalizing resources [?]. These results suggest that athletes may weaken contagion effects of opponents' actions by inhibiting mirror neuron system activity. This regulatory mechanism may have evolutionary adaptability: in resource competition, inhibiting contagion can prevent behavior patterns from being predicted by opponents.

In competitive sports, athletes need to use predictions to break opponents' rhythms rather than passively follow them. Contagion effects may manifest as "motor resonance of action rhythms," but high-level athletes utilize predictive information to transform this resonance into a tool for disrupting opponents' rhythms. Even in stress responses within extremely short timeframes, brief action imitation may occur but immediately differentiates afterward. However, when observed actions mismatch their own predicted outcomes, athletes correct internal models based on prediction errors, which may delay subsequent actions and reduce motor performance.

Therefore, in competitive sports, whether athletes' action patterns converge depends on competitive goals and strategies. Low-level athletes may exhibit action imitation, while high-level athletes transform contagion effects into "reverse control" through prediction, with action patterns showing targeted differentiation or even deliberate creation of "false synchronization" to deceive opponents.

4.2 Neurorehabilitation: Mirror Therapy and Predictive Interventions

The neural mechanisms of motor contagion provide innovative intervention strategies for motor function remodeling after neural injury. Based on the activation characteristics of the mirror neuron system and the dynamic regulatory capacity of predictive processing, modern rehabilitation medicine gradually combines traditional physical therapy with neuroplasticity treatments to improve rehabilitation efficacy.

Action Observation Therapy is a form of mirror therapy. This approach promotes neuroplasticity and rebuilds damaged neural networks through systematic visual-motor coupling, demonstrating significant effectiveness particularly in stroke rehabilitation. A multicenter randomized controlled trial showed that chronic stroke patients exhibited significant improvements in upper limb motor function after four weeks of action observation therapy, with fMRI revealing significantly increased activity in bilateral ventral premotor cortex, bilateral superior temporal gyrus, supplementary motor area, and contralateral supramarginal gyrus during independent movement tasks [?]. This rehabilitation therapy, based on mirror neuron system and brain plasticity principles, activates patients' mirror neurons through action observation, promotes motor cortex remodeling and functional reorganization, and helps restore motor function, representing a scientific and effective rehabilitation treatment method.

Additionally, a multisensory integration-based neurorehabilitation protocol targets the neural circuits of freezing of gait in Parkinson's disease patients through synchronized action observation and sonification techniques. Randomized controlled trials showed that Parkinson' s patients exhibited significantly reduced freezing of gait episode frequency and markedly shortened gait initiation latency after eight weeks of intervention. Therapeutic effects persisted through three-month follow-up periods, with significant improvements also observed in motor disorders, motor problems in daily activities, and physical discomfort [?]. This mirror neuron system-integrated multimodal rehabilitation method can reduce cognitive load, enhance perceptual processes, and promote motor learning, marking a paradigm shift in Parkinson' s rehabilitation from symptom management to neural circuit remodeling and laying the foundation for developing virtual reality scenario transfer and brain-computer interface precision regulation.

Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder characterized by difficulties in social communication and restricted, repetitive patterns of behavior [?]. Traditional screening methods rely on clinical observer subjective ratings or parent interviews (such as ADI-R), which are susceptible to reporter bias and lack sensitivity for young or nonverbal patients. Research has found that children with ASD lack motor contagion ability compared to typically developing children [?]. This provides an innovative direction for early ASD screening. By using motion capture systems to record parameters such as grasping deceleration time and maximum grip aperture, the degree of "interference transfer effect" absence can be quantified, providing objective biobehavioral markers for early ASD screening. Objective behavioral indicators based on motor contagion paradigms (such as action kinematic parameters, prediction error response patterns) may compensate for limitations of traditional screening tools (such as ADI-R or ADOS). Therefore, future research could establish unified experimental protocols (e.g., distractor size, fixation duration) to ensure comparability of screening results, combine EEG or functional near-infrared spectroscopy to record mirror neuron system activation patterns (such as -rhythm suppression) to construct multidimensional screening models alongside behavioral indicators, and utilize deep learning to analyze complex kinematic data (such as nonlinear relationships between grip aperture and deceleration time) to identify ASD-specific patterns.

If successfully translated, motor contagion screening paradigms could compensate for existing tool limitations, providing more sensitive, objective, and minimally invasive diagnostic tools for ASD while laying the foundation for designing personalized rehabilitation programs.

With further research into motor contagion mechanisms, more effective treatment methods and approaches will be discovered, providing new momentum for sports medicine development. For example, predictive processing theory provides a dynamic learning framework for motor function rehabilitation. Future adaptive training programs triggered by prediction errors could accelerate patients' internal model calibration and action control relearning.

4.3 Human-Machine Collaboration: Bio-Inspiration and Ethical Challenges

The theory and mechanisms of motor contagion provide revolutionary ideas for the intelligent design of human-machine collaboration systems. By imitating the biological foundations of human action understanding—such as the resonance characteristics of the mirror neuron system, dynamic tuning capacity of predictive models, and multimodal perceptual integration mechanisms—intelligent agents' interaction capabilities can evolve from passive response to active collaboration.

Specifically, intelligent agents can extract kinematic features (such as joint trajectories, acceleration, and torque distributions) through 3D Convolutional Neural Networks and combine biomechanical constraint optimization algorithms to construct generative models for Active Inference [?]. These models can not only parse spatiotemporal features of actions but also dynamically infer operators' intentions through prediction error minimization, thereby achieving behavioral upgrades from passive response to active collaboration. To further simulate the human brain' s action intention processing, systems can 借鉴 the topological mapping characteristics of ventral premotor cortex to design dynamic weight adjustment modules. These modules enhance the ability to parse ambiguous intentions by integrating visual, tactile, and proprioceptive signals to construct multimodal action representation spaces. Simultaneously, biomechanical constraint optimization algorithms can introduce multi-timescale analytical frameworks combined with functional action classification to optimize system decision-making efficiency. For improved transparency, explanatory generation modules can utilize Bayesian inference results to generate natural language descriptions, providing real-time explanations of action intentions.

Despite significant technological progress, substantial challenges remain. First, contextual generalization ability is limited by cultural specificity and action diversity in training data—for instance, differences in language and gestures across regions may lead to intention misjudgment. Second, ethical safety risks involve privacy protection and responsibility attribution issues [?]. Future research must integrate neuroscientific plasticity mechanisms with meta-learning frameworks from deep reinforcement learning to develop cross-cultural adaptive models. For example, through transfer learning integrating multi-population motor databases or introducing neuromorphic computing to simulate dynamic synaptic weight adjustments, ultimately constructing human-machine collaboration ecosystems that conform to symbiotic ethics.

5.1 The Necessity of the Mirror System: Essential Engine or Replaceable Node?

Since mirror neurons were discovered in the ventral premotor cortex of monkeys, this neural system has been endowed with important functions for interpreting action imitation and understanding. The characteristic that mirror neurons are activated both when individuals perform actions and when observing others perform the same actions provides a physiological basis for the "observation-execution" shared representation theory and quickly became the core mechanism for explaining motor contagion. For example, both common-coding theory and direct matching hypothesis emphasize that the essence of motor contagion is the mirror neuron system' s direct mapping of observed actions onto one' s own motor representations to achieve action imitation or understanding [?, ?]. This view was confirmed in early experimental studies. However, with the deepening development of cognitive neuroscience, the explanatory framework for motor contagion has gradually become more complex. Research has found that humans can trigger contagion not only through biological actions but also through non-biological cues [?].

Furthermore, Ikegami et al.' s [?] baseball experiment found that observers did not simply imitate actions but adjusted internal models through prediction errors, leading to action deviation. This process relies more on predictive networks in premotor cortex, prefrontal cortex, and cerebellum rather than direct mapping of the mirror system. If mirror neurons were a necessary prerequisite, such deviation phenomena could not be explained. These findings have generated a core controversy: Are mirror neurons necessary conditions for constituting motor contagion? Or are they merely replaceable components in a complex cognitive network? The focus of controversy concerns not only the analysis of neural mechanisms but also challenges the necessity of transforming motor contagion theory from a "mirror-centered" to a "system dynamic interaction" paradigm.

Traditional mirror theory emphasizes the "bottom-up" characteristic of motor contagion, where visual input directly activates corresponding motor representations [?]. Emerging views posit that motor contagion results from competition and integration among multiple systems including perception, prediction, and social cognition [?]. For example, the dual-route model proposes that motor contagion results from the combined action of automatic pathways (mirror neuron system) and conscious pathways (prefrontal regulation) [?]. However, predictive processing theory further views motor contagion as dynamic regulation between internal models and perceptual inputs. In this framework, mirror neurons are merely nodes in information flow whose functions may be overridden by high-level regulation. For example, hammer throw athletes' throwing deviations are unrelated to the mirror neuron system but rather represent probabilistic simulation of action outcomes in premotor cortex [?], demonstrating that high-level contagion can be independently achieved through predictive mechanisms.

The core of current controversy is not to deny the role of mirror neurons but to reposition their role in complex cognitive networks. Therefore, future research could construct hierarchical models to distinguish neural bases of low-level (mirror-driven) and high-level (prediction-driven) contagion and quantify their interaction weights. Combining neural intervention, computational modeling, and behavioral analysis to dynamically track contributions of different systems during contagion processes may reveal that mirror neurons are perhaps the "starter" but absolutely not the "only engine" of motor contagion. Only by moving beyond the "necessary or not" framework can we more comprehensively reveal the dynamic nature of the human motor system in imitation, prediction, and innovation.

5.2 Methodological Limitations: The Gap Between Laboratory Paradigms and Ecological Validity

Despite significant theoretical breakthroughs and neural mechanism analyses in motor contagion research, its methodological design still has numerous limitations, particularly regarding the gap between laboratory paradigms and real social scenarios' ecological validity, simplification of experimental tasks, and limitations of measurement tools and explanatory power that urgently require reflection and optimization.

First, existing research mostly relies on highly controlled laboratory tasks. While such designs can precisely manipulate variables, they struggle to simulate the dynamics and complexity of real-world scenarios. For example, Ikegami et al.' s [?] baseball experiment artificially created prediction error conditions by isolating visual feedback with opaque glasses, a control that may weaken participants' ability to integrate multimodal information in real competitions. Similarly, Gray and Beilock' s [?] study of contagion effects through non-action physical cues, while revealing the flexibility of predictive systems, did not involve social cognitive factors in real interpersonal interactions. These simplified designs may cause systematic deviations between experimental results and contagion mechanisms in real contexts, limiting external validity.

Second, current research often isolates action observation and execution tasks as separate events, ignoring dynamic feedback loops in social interaction. For instance, Sparks et al.' s [?] study modulated contagion effects through vocabulary priming, revealing the regulatory role of social contexts, but its static priming paradigm struggles to reflect real-time strategy adjustments in authentic situations. Additionally, most experiments focus on short-term behavioral responses (such as reaction times or motor-evoked potentials), lacking tracking of long-term training or experience accumulation. This decontextualized task design may underestimate the adaptability and plasticity of motor contagion.

Furthermore, existing research relies on reaction times, kinematic parameters, or brain imaging techniques to capture contagion effects, but these indicators cannot comprehensively reflect multi-level cognitive processes. For example, while mirror neuron system activation provides evidence for common-coding theory, it cannot distinguish neural representation differences between automatic imitation and strategic adjustment. Similarly, action deviation triggered by prediction errors may involve interactions between prefrontal regulation and cerebellum-mediated error adjustment, but existing paradigms rarely integrate multimodal physiological indicators, leading to fragmented mechanistic explanations.

Addressing these limitations requires methodological innovation from multiple dimensions. Future research should use virtual reality technology to simulate real scenarios, integrate multi-sensory inputs (such as visual, auditory, or tactile), and dynamically track the evolution of contagion effects in continuous interactions to enhance ecological validity. Second, designing longitudinal studies to compare long-term behavioral and neuroplasticity changes between novices and experts can reveal developmental trajectories and population heterogeneity of contagion mechanisms. Additionally, integrating brain imaging, physiological signals, and behavioral modeling to construct computational models quantifying competitive weights between automatic and conscious pathways will help overcome limitations of single indicators. Naturalistic paradigms can also be introduced to compensate for over-simplification in laboratory controls, making research more closely approximate real-world situations.

In conclusion, methodological limitations do not negate existing achievements but reveal potential space for theoretical deepening and technological innovation. Only by bridging the gap between laboratory and real world can motor contagion research advance from "phenomenon description" to "mechanism prediction," laying a more solid scientific foundation for interdisciplinary applications.

6 Summary and Outlook

As the neural basis of human social interaction, motor contagion research not only reveals deep coupling mechanisms between action systems and social cognition but also challenges traditional mind-body dualism frameworks at the philosophical level. As a core cognitive mechanism connecting perception and action, its theoretical evolution and neural mechanism analysis reveal the complex nature of human action understanding and imitation. This article systematically reviews the dynamic framework of motor contagion from low-level imitation to high-level prediction, emphasizing theoretical integration of the mirror neuron system, predictive processing models, and multi-level network interactions (Figure 1 [Figure 1: see original paper]). Research findings indicate that motor contagion is not the product of a single neural mechanism but rather the result of dynamic coupling among perceptual systems, motor systems, and social cognitive networks. While the mirror neuron system plays a foundational role in shared representation of action observation and execution, its function must be understood within the broader framework of predictive error regulation and conscious pathway competition. Predictive processing theory provides a computational perspective for explaining directional differences in contagion effects, revealing the central role of internal model calibration in action adjustment. Social contexts can regulate contagion intensity, indicating that motor contagion may possess adaptive functions endowed by evolution.

Figure 1 Schematic diagram of hierarchical relationships in motor contagion

After years of development, motor contagion research has moved from single theoretical explanations toward integrated paradigms of interdisciplinary cross-fertilization, constructing multi-level explanatory chains and driving methodological innovations such as combining virtual reality with biomechanical feedback, tactical optimization through multi-agent models, and neural regulation techniques based on brain-computer interfaces. Future research needs to construct dynamic weighting models to quantify interactive effects of situational complexity, emotional states, and social cognition on neural resource allocation. Additionally, existing research is mostly based on Western industrialized society samples, neglecting the shaping role of cultural backgrounds on motor contagion. Current cross-cultural research suffers from "Western-centrism," with experimental paradigms mostly based on Western social contexts and failing to encompass localized interaction forms (such as the collective implications of Chinese Tai Chi). Future research requires global multi-center collaboration, combining anthropological field investigations with neuroimaging techniques to construct culturally sensitive theoretical models.

Motor contagion research is currently in a rapid development stage of interdisciplinary cross-fertilization. Its theoretical reconstruction and application expansion cannot proceed without continuous in-depth decoding from neuroscience, while also requiring consideration of humanistic concerns from social sciences and prudent attention to technological ethics to promote deep integration and collaborative development across multiple disciplines. From infants' imitation instincts to globalized virtual collaboration, from evolutionarily endowed resonance capabilities to civilization-tamed inhibition strategies, motor contagion profoundly reflects the survival wisdom of humans as social species. Future exploration must be conducted within dynamic interactive cognitive frameworks. Motor contagion manifests both as biologically encoded mechanisms of neural circuits and as shaped processes of social cognition. More profoundly, it reveals the eternal dialectical relationship between individual freedom and group interdependence in the human existential condition. Only by breaking the binary opposition between biological determinism and cultural constructivism can we construct a complete cognitive schema. This multi-dimensional ontological characteristic requires researchers to establish interdisciplinary analytical models that reconsider the dual generative logic of human behavior patterns through the interaction between embodied cognition and cultural representation.

Note: Figure translations are in progress. See original paper for figures.

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