International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Scholarly Publisher
RS Global Sp. z O.O.
ISNI: 0000 0004 8495 2390

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ARTICLE TITLE	THE ROLE OF THE MIRROR NEURON SYSTEM IN THE ACQUISITION OF EMERGENCY MEDICINE PROCEDURAL SKILLS: A COMPREHENSIVE NARRATIVE REVIEW
DOI	https://doi.org/10.31435/ijitss.4(48).2025.4459
RECEIVED	30 October 2025
ACCEPTED	20 December 2025
PUBLISHED	26 December 2025
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THE ROLE OF THE MIRROR NEURON SYSTEM IN THE ACQUISITION OF EMERGENCY MEDICINE PROCEDURAL SKILLS: A COMPREHENSIVE NARRATIVE REVIEW

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ABSTRACT

Background: Emergency medicine requires precise and rapid execution of high-risk procedures in time-sensitive environments, leaving limited opportunities for safe supervised practice. Neuroscientific discoveries, particularly related to the mirror neuron system (MNS), suggest that observational learning may effectively enhance motor skill acquisition without risk to patients.
Aim: To comprehensively review the neurobiological foundations, educational applications, and practical implications of the MNS in emergency medicine procedural training.
Material and methods: Narrative review including PubMed, Scopus, Web of Science. Literature (2000–2024) concerning neuroscience, medical education, motor learning, and emergency medicine was analyzed.
Results: Studies demonstrate that the MNS supports imitation, enhances procedural memory formation, and strengthens early motor skill acquisition. Educational strategies such as expert modeling, action observation, motor imagery, and multimodal simulation appear aligned with MNS activation and may optimize procedural training.
Conclusions: The MNS offers a valuable, underutilized framework for optimizing procedural training in emergency medicine. Future research should integrate neurophysiological tools into educational research to directly examine the mechanisms by which observational learning enhances clinical performance.

KEYWORDS

Mirror Neuron System, Emergency Medicine, Motor Learning, Simulation, Medical Education, Action Observation

CITATION

Kateryna Shtohryn, Szymon Rudawski, Magdalena Zięba, Magdalena Morytko, Maja Elertowicz, Mikołaj Moskwa, Patrycja Herod, Aleksandra Wójciak. (2025) The Role of the Mirror Neuron System in the Acquisition of Emergency Medicine Procedural Skills: A Comprehensive Narrative Review. *International Journal of Innovative Technologies in Social Science*. 4(48). doi: 10.31435/ijitss.4(48).2025.4459

Introduction

Emergency medicine (EM) is a procedurally intensive specialty in which clinicians must rapidly master a broad range of invasive and instrument-based techniques, including airway management, central venous access, thoracostomy, and point-of-care procedures often under conditions of time pressure and physiological instability. Traditional training models rely on supervised practice, simulation-based instruction, and expert feedback. While effective, these methods are constrained by patient-safety concerns, variable clinical exposure, limited faculty availability, and logistical barriers within busy emergency departments (Wayne et al., 2008; Cook et al., 2011). Consequently, there is growing interest in augmenting existing approaches with strategies that enhance early cognitive encoding and motor planning before hands-on performance.

One increasingly studied mechanism is observational learning, supported by the mirror neuron system (MNS)—a neural network that activates both when an individual acts and when they observe another person performing the same action. First identified in the ventral premotor cortex (area F5) of macaque monkeys (di Pellegrino et al., 1992; Gallese et al., 1996) and later demonstrated in humans using neuroimaging and neurophysiological methods (Iacoboni et al., 1999; Rizzolatti & Sinigaglia, 2010), the MNS is thought to underlie imitation, action understanding, and motor learning. These processes are directly relevant to procedural medicine, where trainees routinely observe expert clinicians before attempting skills independently. Action observation (AO) and motor imagery (MI) have been shown to engage shared neural substrates with physical practice, facilitating motor acquisition and performance (Jeannerod, 2001; Vogt et al., 2013).

Emerging evidence from surgery, anesthesia, and rehabilitation suggests that structured AO, expert modeling, first-person video perspectives, and integrated AO-plus-simulation interventions can improve procedural accuracy, decrease cognitive load, and accelerate skill acquisition (Arora et al., 2011; McBride et al., 2021; Buccino, 2014). However, these approaches have been underutilized in EM education despite their heavy procedural demands and the natural fit between real-time observation and the MNS-based framework for learning.

This narrative review aims to:

(1) summarize the neurophysiological basis of the human mirror neuron system;

(2) examine behavioral and interventional evidence on AO and MI in motor learning;

(3) evaluate applications of these strategies within medical training disciplines; and

(4) propose practical, MNS-informed recommendations for enhancing procedural education in emergency medicine.

By bridging cognitive neuroscience with EM pedagogy, this review highlights opportunities to integrate biologically grounded learning methods into existing training paradigms.

Materials and Methods

A narrative review methodology was selected because the topic spans multiple domains—neuroscience, motor learning theory, and medical education—requiring an integrative and concept-driven approach rather than a strictly systematic design. A comprehensive literature search was conducted using PubMed, Scopus, and Web of Science. Search terms included combinations of: *mirror neuron system*, *motor learning*, *observational learning*, *action observation*, *medical education*, *simulation training*, and *emergency medicine*.

Studies were eligible for inclusion if they addressed one or more of the following domains:

(1) neurobiological foundations of the mirror neuron system;

(2) observational learning, imitation, action observation, or motor imagery in educational or motor-learning contexts;

(3) simulation-based training within medical or surgical education; or

(4) procedural performance or skill acquisition relevant to emergency medicine practice.

Exclusion criteria were: (a) non-English publications; (b) articles not related to procedural or motor learning; and (c) papers focusing exclusively on psychological or theoretical constructs without clear neurobiological relevance.

The search identified more than 160 abstracts. After initial screening, 71 full-text articles were reviewed in detail, of which 42 met all inclusion criteria and were incorporated into this narrative synthesis.

Results

The final dataset consisted of 42 included studies, representing neuroscience, cognitive psychology, rehabilitation research, and medical education. Across these sources, four recurring themes were identified: (1) neurophysiological foundations of the mirror neuron system (MNS), (2) behavioral effects of action observation (AO) and motor imagery (MI) on motor learning, (3) educational applications of MNS-based strategies, and (4) implications for emergency medicine procedural training. imitation of complex motor sequences;

1. Neurophysiological Foundations of the Mirror Neuron System

Neurophysiological studies provide strong evidence that the MNS supports internal motor simulation during action perception. Modulation of corticospinal excitability (CSE) during action observation is one of the most consistent findings. Naeem et al. (2014), synthesizing multiple TMS experiments, demonstrated two characteristic phases of CSE modulation: an early, non-specific facilitation (~90 ms) and a later, muscle-specific facilitation (~200 ms), indicating that observed actions are rapidly mapped onto corresponding motor representations.

The intention underlying observation significantly alters neural activation patterns. Catmur et al. (2012) showed that contextual cues—such as whether the observer intends to imitate—shape sensorimotor responses during action observation. These findings build on earlier foundational work demonstrating that simple observation of goal-directed actions increases motor cortex excitability (Fadiga et al., 1995). Together, this research supports a model in which the MNS dynamically integrates perceptual, contextual, and intentional information to prepare internal motor programs.

Longitudinal studies reveal that different forms of observation have distinct effects. Labruna et al. (2012) reported that repeated sessions of motor imagery produced sustained increases in CSE, particularly in the non-dominant hemisphere, whereas facilitation from pure observation plateaued earlier. These findings underscore the importance of combining observation with active cognitive simulation to promote neuroplasticity relevant to motor learning.

2. Behavioral Evidence: Effects of AO and MI on Motor Learning

Behavioral studies consistently demonstrate that AO and MI enhance motor learning, especially when used concurrently. In a controlled TMS experiment, Wright et al. (2014) showed that AO+MI produced significantly greater MEP amplitudes than observation alone, confirming stronger motor system engagement. This facilitation was muscle-specific and temporally aligned with the observed action—an indicator of precise motor representation formation.

Additional work has shown that cognitive factors modulate imitation quality. A study examining voluntary imitation reported that directing attention to movement kinematics or imagining the action improved reproduction of timing and amplitude compared to passive viewing (Experimental Brain Research, 2016). These results reinforce the idea that the MNS interacts with top-down cognitive processes during observational learning.

Further evidence comes from Eaves et al. (2020), who compared congruent AO+MI, incongruent AO+MI, and pure AO. Congruent AO+MI yielded the strongest CSE facilitation, while incongruent AO+MI produced attenuated responses. Pure observation produced inconsistent facilitation effects. These findings highlight that alignment of observed and imagined actions is critical, suggesting that procedural training should synchronize AO with guided MI to maximize learning benefits.

3. Educational Applications in Clinical and Medical Training

Although most educational evidence comes from rehabilitation science rather than emergency medicine, these studies provide compelling support for MNS-based instructional methods. A systematic review by Brunner et al. (2015) found that action observation training (AOT) improves motor recovery across neurologic and orthopedic conditions. The most effective interventions included repeated exposure to expert models, progressive task difficulty, and explicit attention to movement phases—principles directly transferable to medical skills training.

Similarly, clinical trials involving stroke survivors indicate that combining AO, MI, and physical practice yields superior motor and cognitive outcomes compared to standard therapy alone (Jung et al., 2020). These effects likely reflect activation and strengthening of MNS-related circuits responsible for action understanding and motor planning.

From an instructional design perspective, studies recommend structuring observation in first-person perspective, decomposing skills into meaningful segments, and incorporating mental rehearsal to reinforce internal motor simulation (Wright et al., 2014; Cunnington & Vogt, 2013). These design principles align naturally with the sequential, high-precision nature of emergency procedures.

4. Implications for Emergency Medicine Procedural Training

While direct studies in emergency medicine (EM) remain limited, the converging neurophysiological and behavioral evidence suggests that MNS-enhanced training could substantially benefit procedural skill acquisition. Emergency procedures—such as airway management, vascular access, thoracostomy, and resuscitation tasks—are complex, time-critical, and highly proceduralized, making them well-suited to AO- and MI-based methods.

Simulation programs integrating structured expert video modeling, first-person action observation, cognitive rehearsal, and guided MI may optimize the early phases of skill acquisition by strengthening internal motor representations before hands-on practice. This layered approach aligns with the known stages of procedural memory formation and may reduce cognitive load during initial attempts at high-stakes procedures.

Given the demonstrated neuroplastic effects of repeated AO and MI (Labruna et al., 2012), incorporating these techniques into EM curricula could enhance both skill acquisition and long-term retention. Learner-specific customization—based on imagery ability, prior experience, and procedural complexity—represents a promising avenue for future educational innovation.

Discussion

The findings of this narrative review reinforce the view that the mirror neuron system (MNS) constitutes an essential neurocognitive mechanism that can be purposefully leveraged to improve procedural education in emergency medicine. Across neuroscience, psychology, rehabilitation science, and medical education, the evidence consistently demonstrates that observational learning—particularly when delivered through structured action observation (AO) and motor imagery (MI)—facilitates the encoding, refinement, and consolidation of motor skills. These mechanisms align directly with the procedural demands of emergency medicine, which frequently requires rapid, precise, and high-stakes technical performance.

From a neurobiological perspective, studies employing transcranial magnetic stimulation (TMS), EEG, and fMRI show that observing goal-directed actions elicits patterned activation of sensorimotor networks, including muscle-specific facilitation and early motor resonance. This activation appears to prepare the motor system for future execution of the observed skill. The contextual sensitivity of the MNS—modulated by intention, perspective, expertise, and congruency—suggests that observational learning is not a passive process but rather an interactive form of cognitive participation in skill rehearsal. This dynamic adaptive response may be particularly beneficial for novices, who benefit from strengthened internal motor representations prior to hands-on practice.

Behavioral studies further demonstrate that combining action observation with motor imagery yields greater improvements in motor activation, learning accuracy, and skill retention than either strategy alone. These synergistic effects appear to result from the simultaneous engagement of visual, kinesthetic, and predictive coding networks responsible for procedural planning and motor sequencing. Notably, interventions using first-person expert modeling, stepwise procedural decomposition, and guided imagery instruction produce the strongest outcomes—highlighting the importance of thoughtful educational design.

In the field of emergency medicine, these findings have clear relevance. EM training is constrained by unpredictable clinical exposure, faculty workload, patient-safety concerns, and the limited availability of supervised procedural opportunities. In this context, MNS-based strategies offer a practical, low-cost, scalable means to support early phases of psychomotor skill acquisition. Structured AO-MI modules could be embedded into simulation curricula, online preparatory materials, or pre-procedure briefings. For example, learners preparing for endotracheal intubation or thoracostomy could engage in guided AO+MI sequences that facilitate internal motor simulation before approaching a manikin or patient.

Furthermore, the integration of MNS-informed strategies aligns with broader trends in innovative educational technologies, including VR-based procedural training, augmented reality overlays, and mixed-modality simulation. These tools inherently rely on observational and immersive learning, making the incorporation of AO-MI principles both feasible and pedagogically coherent. In the context of the social sciences, the application of MNS-based frameworks represents an innovative intersection between cognitive neuroscience and professional skill development—highlighting the translational value of neurobiological knowledge for improving educational equity, access, and efficiency across high-risk disciplines.

However, limitations remain. Most neurophysiological studies use controlled laboratory actions rather than complex procedural tasks. Most educational research comes from rehabilitation or surgery rather than emergency medicine. Thus, direct empirical evidence within EM is still needed. Nevertheless, the theoretical coherence across domains strongly suggests that EM stands to benefit significantly from adopting MNS-aligned training approaches.

Conclusions

This review demonstrates that the mirror neuron system provides a compelling neurobiological foundation for observational learning and motor skill acquisition relevant to emergency medicine. Evidence from neuroscience and medical education indicates that action observation, motor imagery, and structured expert modeling enhance motor learning by strengthening internal sensorimotor representations. Although direct studies in emergency medicine are limited, the theoretical rationale and empirical support from related fields suggest substantial potential for integrating MNS-aligned strategies into EM procedural training. Future research should systematically evaluate these approaches within EM curricula and explore neurophysiological correlates of procedural learning to advance evidence-based training methods.

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