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The role of attention in motor control and learning

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Performing and learning motor behaviors are fundamental to everyday life. The relations between perceptual input and motor output have been studied and are well understood for simple experimental settings. Recent findings, however, suggest that motor actions also critically depend on cognitive factors; these influences are most notable in complex environments that place high demands on attention and memory. In this review, the role of various aspects of attention in motor control is discussed, focusing on the following points: (1) recent findings concerning interactions between attentional resources and motor skill acquisition, (2) the consistency of attentional states (divided versus focused) and motor memory retrieval, and (3) the locus of attention (internal versus external) and motor performance. These findings collectively highlight the interplay between attention and motor systems, which in turn has practical implications for developing and improving motor training and rehabilitation programs.

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Acquiring, performing, and remembering pertinent motor skills are integral to daily life. Importantly, motor skills are often performed in environments with high attentional demands. For example, during an emergency, a pilot must simultaneously operate the aircraft, assess its current integrity, and also maintain communications with ground authorities. Similarly, a stroke patient recovering the ability to walk also has to divide her/his attention to cars, other pedestrians, and obstacles in the path in order to avoid collisions. Performing such actions in complex environments requires seamless coordination among multiple processes to extract sensory information, learn task features, control motor commands, and make a strategic decision [1–3].

Historically, this integrated process has largely been studied by isolating specific subprocesses proposed by an information-processing framework: sensory information serves as input that is then used to construct an internal representation of the world to guide decisions, and these commands are executed via motor output. Under this conventional, compartmentalized approach, it is not surprising that there has been little consideration of cognitive influences on motor control (and vice versa) [4]. For instance, motor control research has focused on factors such as biomechanics, postural control, and reflexive constraints, which are directly related to the neuromuscular system; conversely, the cognitive literature has largely focused on factors such as attention, working memory, and decision-making – processes not typically regarded to be relevant for understanding motor performance. Importantly, however, accumulating recent evidence suggests that various cognitive factors may impose fundamental constraints on the acquisition and performance of movements [5•,6,7••,8].

In complex, real world environments, we must select and attend to goal-relevant information with limited cognitive resources while concurrently performing different actions. This review focuses on three major topics emphasizing the role of attention in motor learning and performance: (1) how attentional demands influence motor skill acquisition, (2) how the consistency of attentional states (e.g. divided versus focused) between motor learning and recall impacts skill transfer across the two phases, and (3) how the locus of attention (e.g. own performance versus performance environment) affects the overall performance. Taken together, these studies highlight the relation between various attentional processes and motor performance and raise several practical implications for designing effective motor training programs. Furthermore, they demonstrate how considering mutual influences between cognition and action can provide exceptional research opportunities to enhance our understanding of adaptive human behaviors in real life.

Attentional demand on acquisition of motor skills

To learn a new motor skill like a tennis serve, we monitor performance to detect and evaluate movement errors, and also identify key transformations that map sensory experience to update internal models for future use [9]. In such a setting, attention is commonly viewed as a necessary capacity-limited resource that facilitates multiple cognitive functions and resolves competition between these processes [10–12]. To investigate whether and how attentional demands influence motor skill learning, previous studies typically used a dual-task paradigm. In this paradigm, the impairment of motor performance due to the concurrent secondary task is regarded as evidence for the necessity of attentional resources in skill acquisition. Secondary tasks in such studies range from tone counting to mental arithmetic [13–18]. For example, many of these studies demonstrate that performance in a serial reaction time task (SRT), where participants are trained to press a series of cued keys as quickly as possible, is impaired by the secondary task. In particular, these studies show that participants fail to learn the underlying repeated sequence when they divide attention to a secondary task. This result is largely consistent with the notion that attention is an information-processing resource involved in acquiring new motor skills [13–15].

Dual-task deterioration of motor performance was also observed in other types of motor learning, including sensorimotor adaptation and dynamic force adaptation, in which different functional and neural mechanisms are involved in sequence learning [19,20]. For instance, Redding *et al.* [21] showed that simultaneously performing a secondary cognitive task impaired the accuracy of pointing in a prism adaptation task, in which the visual field was laterally displaced. Taylor and Thoroughman [17] further specified which motor control process is impaired by the secondary task during force-field adaptation. In this task, participants were required to compensate for the force-induced errors during the movement and to use this information for later movements. They demonstrated that divided attention did not impair the within-movement feedback control, but did reduce subsequent movement adaptation. This suggests that divided attention to the secondary task interferes with a predictive motor control process operating across trials. In a subsequent task, they also showed that the degree of cognitive burden imposed by a secondary task resulted in a proportional degradation of motor adaptation [16].

To summarize, while participants need to monitor movements, evaluate errors, and update an internal model, consistent impairments observed in a wide range of motor learning tasks by dividing attention to a cognitive task. These results clearly demonstrate that attentional resource plays a critical role in motor skill acquisition [22••].

Attentional states for motor memory

The studies mentioned thus far demonstrate how allocating attentional resource to a concurrent task interferes with sequence learning, sensorimotor adaptation, and force-field learning [13–17]; however, these previous studies focused mainly on how divided attention impairs immediate motor performance, thereby not considering how it affects memory formation and retrieval. According to recent work [23,24,25•,26], the success of motor memory retrieval depends on whether participants consistently perform the secondary task during motor learning and later recall stages, independent of available attentional resources per se. Specifically, Song and Bédard [25•] asked participants to perform a visuomotor adaptation task either with or without a concurrent task (e.g. rapid serial visual presentation; RSVP). They observed that performing the dual-task itself did not affect impair immediate performance. Yet, when participants were tested later during the recall phase, a motor skill learned under the dual-task was remembered only when a similar secondary task was present. When participants were tested without the secondary task, their performance reverted to untrained levels as though the motor task had not been learned in the first place. Hence, this paradoxical result, in which the level of performance decreases when more attentional resources are available, suggests that while the secondary task does not interrupt motor memory formation, the dual-task context, or the lack thereof, acts as a vital context for learning. Interestingly, this task-context-dependent 'savings' in motor learning was evident even when the specific secondary task or sensory modality differed between learning (e.g. RSVP) and recall (e.g. sound discrimination). Thus, the general state of dividing attention during the dual-task, but not the specific parameters of stimuli, is associated with motor memory.

This reinstatement of attentional-context in visuomotor memory retrieval appears to operate similarly to the environmental context in episodic memory retrieval experiments that demonstrate benefits of having learning and recall take place in consistent environmental contexts, highlighting encoding-specificity of episodic memory [27–29]; however, a notable difference is that consistent attentional contexts may form an internal cue that overrides the external environmental cue formed by different secondary tasks. Hence, as long as the attentional context integrated during motor memory formation is consistent learned motor skills can be retrieved even if the specific external environmental context is altered at recall [23,25•,26].

In addition to consistent external contexts, previous studies have reported that consistent internal physiological states induced by alcohol, morphine, cigarettes, or nitric oxide can improve episodic memory recall in both humans and animals [30–33]. It appears that performing a motor task alone or with a cognitive task can also instantiate a similar but different internal context without drug-induced physiological changes and can gate the retrieval of visuomotor memory. Perhaps attentional context itself leads to changes in internal physiological states similar to those induced by drugs. Future research is required to fully understand whether modulation of motor memory by attentional contexts and that of episodic memory by physiological states is driven by common or distinct mechanisms.

It is equally important to understand whether this newly discovered paradoxical benefit of consistent distraction is transient or sustained because it would determine its impact on the development of long-term motor skills. Im *et al.* [24] showed that this attentional context forms a long-term internal context affecting visuomotor performance on the following day. This long-term modulation by consistent attentional state is consistent with other studies reporting that past experience of a specific attentional set and strategy — even during a brief exposure — can lead to a long-lasting influence on one's strategy and attentional set [34–36]. Such long-lasting learning effects are conceptualized as automatic activation of associations formed between attentional sets and the environmental context [37,38]. Moreover, the consistency of attentional states also determines the success of generalization of motor behaviors. Wang and Song [26] showed that switching the attentional state from training (dual-task) to generalization (single-task) reduced the range of transfer of visuomotor adaptation to untrained directions. Yet, when consistent distraction was present throughout training and generalization, visuomotor generalization was equivalent to when distractions were absent. This result indicates that the integrated attentional state and memory in one setting can transfer and extrapolate motor skills to a wide range of new settings.

If this association of attentional state and visuomotor memory gates the success of visuomotor memory retrieval, another remaining question concerns when and how it is formed. Two classic models of associative learning [39] might propose different hypotheses about when the association of attentional state and visuomotor memory is formed. Mackintosh [40] suggested that the associability of a stimulus and outcome is determined by how accurately it predicts reinforcement (*predictability hypothesis*). Alternatively, Pearce and Hall [41] postulated that attention to uncertainty results in the high associability. Therefore, once learning has reached a stable asymptote, no further attention to the stimulus is required and the associability declines (*uncertainty hypothesis*). Im *et al.* [23] revealed that the association of attentional state and visuomotor memory occurs in the early phase of motor learning, in which motor error reduces rapidly and requires considerable cognitive effort for adjustment of motor commands rather than in the late phase, in which motor performance becomes more efficient and automatic [42–44]. This result appears to be consistent with the uncertainty account [41].

Taken together, these studies show that attention plays a critical role during sensorimotor learning in selecting sensory stimulation and integrating it with motor memory beyond simply providing resources for learning. In turn, findings showing that the consistency of attentional states during learning and recall facilitates retrieval of visuomotor memory also have potential practical implications for developing and improving motor training programs. If such an arbitrary association of attentional state and visuomotor memory persists beyond the 1-hour experimental session and can be generalized to untrained situations, it is likely that associations formed during motor learning outside the lab in the real world would also have a durable time course and generalizability that could significantly benefit everyday motor learning performance. Therefore, without consideration of internal task contexts in real-life situations, the success of learning and rehabilitation programs may be undermined.

Attentional focus and performance outcomes

In addition to considering whether and how to divide attention among several activities, we often need to decide where to engage our attention during motor performance. An intriguing question remains regarding how attentional focus affects movement and performance outcomes: is it better to focus attention on our own movements (i.e. internal focus) or on the effects our movements have on the environment (i.e. external focus)? Here, we discuss practical implications of the locus of attention for optimizing motor performance and learning.

Accumulated evidence supports the latter suggestion: adopting an external focus on the intended movement is more beneficial relative to an internal focus on body movements [45•,46]. For instance, Wulf *et al.* [47] demonstrated that balance learning was enhanced when participants focus on the markers attached to a balance platform as opposed to their feet. These differential effects of internal versus external foci have been mainly explained within the constrained action hypothesis [48]. According to this hypothesis, internal focus induces a conscious type of control, which, in turn, causes performers to constrain their motor system by interfering with automatic control processes. In contrast, an external focus promotes a more automatic mode of control, allowing the utilization of unconscious, fast, and reflexive control process. In accord, it has been demonstrated that an external focus not only led to immediate beneficial effects on performance but also on retention and transfer in both movement effectiveness (e.g. accuracy, consistency, balance) and efficiency (e.g. muscular activity, force production, cardiovascular responses) [49]. In accord, a recent TMS (Transcranial magnetic stimulation) study reported that focusing attention internally or externally lead to changes in intracortical inhibition within the primary motor cortex [50].

Other researchers propose that the appropriate focus of attention is determined by the performer's skill level. Specifically, internally focused attention is appropriate for novices who tend to consciously control many of the details associated with performance; in contrast, externally focused attention is better for experts who execute skills automatically without conscious attentional monitoring [51]. According to this view, skilled individuals should show deteriorated performance with an internal focus because they would revert to less automatic form of movement control. This is considered as a basis for *choking under pressure* – a common explanation for performance decrements under high-pressure situations. In other words, increased anxiety exerts efforts to consciously control more complex procedural knowledge that is already automatized [52]. Altogether, these studies consistently demonstrate that the focus of attention can be a critical element determining the success of effective and skilled movements. Thus, it has practical implications for optimizing motor performance in applied and clinical contexts by finding the right approaches for directing attention to effective foci.

Concluding remarks

Here, we reviewed recent progress made to understand the relation between attention, motor performance, and learning, as well as how these factors affect the success of current performance and the development of long-term motor skills. These findings also highlight important practical implications for designing motor learning programs to be more efficient and generalizable to dynamic, real-world settings. This has direct applications for training drivers, pilots, and athletes, as well as the design of motor rehabilitation programs for individuals learning to recover lost motor functions. An understanding of this cross-integration mechanism will help develop a theoretical framework that describes how visual input interacts with attention and memory to generate motor actions. Furthermore, blurring the distinctions and emphasizing the interactions between motor and cognitive processes will in turn contribute to advancing the interdisciplinary fields of cognitive science, neuroscience, and biomedical engineering—all which have traditionally studied cognitive processes and motor control separately.

Conflict of interest statement

Nothing declared.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Wolpert DM, Flanagan JR: **Motor learning**. *Curr Biol* 2010, **20**: R467-472.

2. Clark D, Ivry RB: **Multiple systems for motor skill learning**. *Wiley Interdiscip Rev Cogn Sci* 2010, **1**:461-467.

3. Seidler RD, Carson RG: **Sensorimotor learning: neurocognitive mechanisms and individual differences**. *J Neuroeng Rehabil* 2017, **14**:74.

4. Rosenbaum DA: **The Cinderella of psychology: the neglect of motor control in the science of mental life and behavior**. *Am Psychol* 2005, **60**:308-317.

5. • Gallivan JP, Chapman CS, Wolpert DM, Flanagan JR: **Decision-making in sensorimotor control**. *Nat Rev Neurosci* 2018, **19**:519-534

This review paper presented recent research in human sensorimotor, supporting that sensorimotor networks are closely involved in decision-making process through simultaneous evaluation of alternative activities in concert with widely distributed perceptual and cognitive systems.

6. Song JH, Nakayama K: **Hidden cognitive states revealed in choice reaching tasks**. *Trends Cogn Sci* 2009, **13**:360-366.

7. •• Song JH: **Abandoning and modifying one action plan for alternatives**. *Philos Trans R Soc Lond B Biol Sci* 2017, **372**

This review paper illustrated how investigations using combined cognition and action provide exceptional research opportunities that will enhance our understanding of a wide range of behavioral and brain mechanisms — common to humans and other animals — that support seamless coordination of behavior in the complex world.

8. Cisek P, Kalaska JF: **Neural mechanisms for interacting with a world full of action choices**. *Annu Rev Neurosci* 2010, **33**:269-298.

9. Shadmehr R, Smith MA, Krakauer JW: **Error correction, sensory prediction, and adaptation in motor control**. *Annu Rev Neurosci* 2010, **33**:89-108.

10. Wickens CD, Kessel C: **Processing resource demands of failure detection in dynamic systems**. *J Exp Psychol Hum Percept Perform* 1980, **6**:564-577.

11. Friedman A, Polson MC, Dafoe CG, Gaskill SJ: **Dividing attention within and between hemispheres: testing a multiple resources approach to limited-capacity information processing**. *J Exp Psychol Hum Percept Perform* 1982, **8**:625-650.

12. Pashler H: **Divided attention: storing and classifying briefly presented objects**. *Psychon Bull Rev* 1994, **1**:115-118.

13. Curran T, Keele SW: **Attentional and nonattentional forms of sequence learning**. *J Exp Psychol Learn Mem Cogn* 1993, **19**:189-202.

14. Nissen MJ, Bullemer P: **Attentional requirements of learning: evidence from performance measures**. *Cogn Psychol* 1987, **19**:1-32.

15. Frensch PA, Lin J, Buchner A: **Learning versus behavioral expression of the learned: the effects of a secondary tone-counting task on implicit learning in the serial reaction task**. *Psychol Res* 1998, **61**:83-98.

16. Taylor JA, Thoroughman KA: **Motor adaptation scaled by the difficulty of a secondary cognitive task**. *PLoS One* 2008, **3**: e2485.

17. Taylor JA, Thoroughman KA: **Divided attention impairs human motor adaptation but not feedback control**. *J Neurophysiol* 2007, **98**:317-326.

18. Leone C, Feys P, Moumdjian L, D'Amico E, Zappia M, Patti F: **Cognitive-motor dual-task interference: a systematic review of neural correlates**. *Neurosci Biobehav Rev* 2017, **75**:348-360.

19. Hikosaka O, Nakahara H, Rand MK, Sakai K, Lu X, Nakamura K, Miyachi S, Doya K: **Parallel neural networks for learning sequential procedures**. *Trends Neurosci* 1999, **22**:464-471.

20. Ghilardi MF, Ghez C, Dhawan V, Moeller J, Mentis M, Nakamura T, Antonini A, Eidelberg D: **Patterns of regional brain activation associated with different forms of motor learning**. *Brain Res* 2000, **871**:127-145.

21. Redding GM, Wallace B: **Adaptive spatial alignment and strategic perceptual-motor control**. *J Exp Psychol Hum Percept Perform* 1996, **22**:379-394.

22. •• McDougle SD, Ivry RB, Taylor JA: **Taking aim at the cognitive side of learning in sensorimotor adaptation tasks**. *Trends Cogn Sci* 2016, **20**:535-544

This paper reviewed the contribution of explicit strategic components to visuomotor adaptation, which has been known to be solely governed by an implicit error-driven mechanism.

23. Im HY, Bedard P, Song JH: **Encoding attentional states during visuomotor adaptation**. *J Vis* 2015, **15**:20.

24. Im HY, Bedard P, Song JH: **Long lasting attentional-context dependent visuomotor memory**. *J Exp Psychol Hum Percept Perform* 2016, **42**:1269-1274.

25. • Song JH, Bedard P: **Paradoxical benefits of dual-task contexts for visuomotor memory**. *Psychol Sci* 2015, **26**:148-158

This study first demonstrated how the consistency of attentional contexts (divided versus focused) can form an internal cue for motor memory. It showed that a motor skill learned under the dual-task was remembered only when a similar secondary task was present. When participants were tested without the secondary task, their performance reverted to untrained levels as if the motor task had not been learned in the first place. This paradoxical result suggests that the dual-task context acts as a vital context for motor memory.

26. Wang TSL, Song JH: **Impaired visuomotor generalization by inconsistent attentional contexts**. *J Neurophysiol* 2017, **118**:1709-1719.

27. Godden DR, Baddeley AD: **Context-dependent memory in two natural environments: on land and underwater**. *Br J Psychol* 1975, **66**:325-331.

28. Smith SM, Vela E: **Environmental context-dependent memory: a review and meta-analysis**. *Psychon Bull Rev* 2001, **8**:203-220.

29. Eich JE: **The cue-dependent nature of state-dependent retrieval**. *Mem Cogn* 1980, **8**:157-173.

30. Blasi V, Young AC, Tansy AP, Petersen SE, Snyder AZ, Corbetta M: **Word retrieval learning modulates right frontal cortex in patients with left frontal damage**. *Neuron* 2002, **36**:159-170.

31. DeCarli C, Haxby JV, Gillette JA, Teichberg D, Rapoport SI, Schapiro MB: **Longitudinal changes in lateral ventricular volume in patients with dementia of the Alzheimer type**. *Neurology* 1992, **42**:2029-2036.

32. Nishimura M, Shiigi Y, Kaneto H: **State dependent and/or direct memory retrieval by morphine in mice**. *Psychopharmacology (Berl)* 1990, **100**:27-30.

33. Peters R, Mcgee R: **Cigarette-smoking and state-dependent memory**. *Psychopharmacology* 1982, **76**:232-235.

34. Leber AB, Egeth HE: **It's under control: top-down search strategies can override attentional capture**. *Psychon Bull Rev* 2006, **13**:132-138.

35. Leber AB, Kawahara J, Gabari Y: **Long-term abstract learning of attentional set**. *J Exp Psychol Hum Percept Perform* 2009, **35**:1385-1397.

36. Thompson C, Underwood G, Crundall D: **Previous attentional set can induce an attentional blink with task-irrelevant initial targets**. *Q J Exp Psychol* 2007, **60**:1603-1609.

37. Cooper R, Shallice T: **Contention scheduling and the control of routine activities**. *Cogn Neuropsychol* 2000, **17**:297-338.

38. Norman D, Shallice T: **Attention to action: willed and automatic control of behavior**. In *Consciousness and Self-Regulation: Advances in Research and Theory IV.* Edited by Davidson R, Schwartz R, Shapiro D. Plenum Press; 1986.

39. Pearce JM, Bouton ME: **Theories of associative learning in animals**. *Annu Rev Psychol* 2001, **52**:111-139.

40. Mackintosh NJ: **Blocking of conditioned suppression: role of the first compound trial**. *J Exp Psychol Anim Behav Process* 1975, **1**:335-345.

41. Pearce JM, Hall G: **A model for Pavlovian learning: variations in the effectiveness of conditioned but not of unconditioned stimuli**. *Psychol Rev* 1980, **87**:532-552.

42. Atkeson CG: **Learning arm kinematics and dynamics**. *Annu Rev Neurosci* 1989, **12**:157-183.

43. Fitts PM, Peterson JR: **Information capacity of discrete motor responses**. *J Exp Psychol* 1964, **67**:103-112.

44. Preilowski B: **Self-recognition as a test of consciousness in left and right hemisphere of "split-brain" patients**. *Act Nerv Super (Praha)* **(19 Suppl. 2)**:1977:343-344.

45. • Lewthwaite R, Wulf G: **Optimizing motivation and attention for motor performance and learning**. *Curr Opin Psychol* 2017, **16**:38-42

This paper discussed multi-level approaches to understand how the locus of attention (internal versus external) influence motivation of motor learning as well as the success of outcomes. The authors listed a series of evidence supporting the advantage of maintaining the internal over external attentional focus during motor performance.

46. Wulf G, Lewthwaite R: **Optimizing performance through intrinsic motivation and attention for learning: the OPTIMAL theory of motor learning**. *Psychon Bull Rev* 2016, **23**:1382-1414.

47. Wulf G, Hoss M, Prinz W: **Instructions for motor learning: differential effects of internal versus external focus of attention**. *J Mot Behav* 1998, **30**:169-179.

48. Wulf G, McNevin N, Shea CH: **The automaticity of complex motor skill learning as a function of attentional focus**. *Q J Exp Psychol A* 2001, **54**:1143-1154.

49. Lohse KR, Jones M, Healy AF, Sherwood DE: **The role of attention in motor control**. *J Exp Psychol Gen* 2014, **143**:930.

50. Kuhn YA, Keller M, Ruffieux J, Taube W: **Adopting an external focus of attention alters intracortical inhibition within the primary motor cortex**. *Acta Physiol (Oxf, Engl)* 2017, **220**:289-299.

51. Beilock SL, Gray R: **From attentional control to attentional spillover: a skill-level investigation of attention, movement, and performance outcomes**. *Hum Mov Sci* 2012, **31**:1473-1499.

52. Mesagno C, Beckmann J: **Choking under pressure: theoretical models and interventions**. *Curr Opin Psychol* 2017, **16**:170-175.