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 are 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 vs. focused) and motor memory retrieval, and (3) the locus of attention (internal vs. 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.

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 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 sub processes 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 [5-8].

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 vs. focused) between motor learning and recall impacts skill transfer across the two phases, and (3) how the locus of attention (e.g., own performance vs. 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 [23-26], 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 & 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 & 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 & 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 arbitrary association of attentional state and visuomotor memory persists beyond the 1-hr 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 vs. 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 [52-55]. 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.

Acknowledgements

This work was supported by NSF CAREER BCS-1555006 to J.H.S. We thank Dr. J.D McCarthy for helpful discussion

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