

## Cognitive Contributions to Adolescent Motor Learning: A Literature Review

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### Abstract

Motor skill acquisition underlies both everyday and specialized human activities, yet individuals differ substantially in the rate at which they learn new movements. Although Fitts and Posner's (1967) three-stage model describes a universal trajectory from conscious to automatic performance, it does not explain why some learners progress through these stages faster than others. Cognitive ability has been proposed as one source of this variability, with working memory (WM) and processing speed implicated as the components most relevant to motor learning. However, most existing research has sampled children or adults, with adolescents underrepresented, and few studies directly compare higher and average-intelligence groups on learning rate rather than final performance. This review outlines currently known contributions of working memory and processing speed to motor learning rate, which appear to vary across learning stages, task types, and practice conditions. Implications for how cognitive ability should be considered in research and practice with adolescent populations are discussed.

*Keywords: Working memory, processing speed, motor sequence acquisition, adolescents*

Movement and physical activities include a wide range of simple to complex motor skills and are required for basic daily functions, and for complex skills and sports, as well as musical activities (Sutapa et al., 2021; Choo et al., 2024). Through practice, individuals can gradually improve the accuracy, efficiency, and consistency of their movements. However, even when people practice under similar conditions, they may differ greatly in how fast they learn the same motor skill. Some learners gain control and accuracy very quickly, while others need much more time and repetition to reach that same level of performance (Anderson et al., 2021; Ranganathan et al., 2022). These differences demonstrate that mastery of a movement, or even sequences of movements, may depend on more than simply the amount of time spent practising. One possible explanation for these differences is variation in cognitive ability, particularly in the mental processes involved in remembering information, processing instructions, monitoring performance, and responding to feedback (Ackerman & Cianciolo, 2000).

Understanding the causes of this variability has practical value for educational and clinical contexts. In educational settings, recognizing individual differences may help teachers and sports coaches to design teaching methods that better accommodate differences between learners (Anderson et al., 2021). In rehabilitation, understanding variation in learning rates may similarly help professionals tailor recovery programmes to individual patients (Shishov et al., 2017). Slower skill acquisition may sometimes be interpreted as reflecting lower ability or lower learning potential. However, motor learning is also sensitive to the conditions under which practice occurs. The difficulty posed by a task can differ according to the learner's current skill level, while instructional and practice conditions can influence subsequent learning (Guadagnoli & Lee, 2004; Anderson et al., 2021). If these influences are overlooked, differences in learning rate may be attributed too readily to cognitive ability. This may lead educators or rehabilitation professionals to underestimate a learner's capacity when changes to the learning conditions could support better outcomes.

Ultimately, discovering why people learn at different speeds can allow professionals to maximize human potential and improve training outcomes. Thus, this review examines two specific cognitive abilities that may contribute to motor learning: working memory and processing speed. The review considers whether specific cognitive abilities show different relationships depending on the type of motor task, the demands placed on the learner, and the way motor learning itself is measured.

### **Changing Cognitive Demands Across Motor Learning**

To explain how people learn movements, Fitts and Posner (1967) proposed a model of skill acquisition consisting of three stages: the cognitive, associative, and autonomous stages. During the cognitive stage, individuals are unfamiliar with the skill and must actively determine how to perform the required movements. Because the task is new, learners typically experience high cognitive demands as they attempt to understand and coordinate the appropriate movement patterns. Performance during this stage may therefore involve frequent errors, inconsistent movements, and strong reliance on conscious attention.

The associative stage occurs as individuals develop a basic understanding of the skill and engage in continued practice to refine their performance. Movements become smoother, more coordinated, and more consistent, while errors generally decrease. Learners also become increasingly capable of detecting and correcting their own performance errors through internal feedback. During the autonomous stage, execution becomes increasingly automatic and consistent and requires less conscious control, allowing attentional resources to be allocated to other aspects of the task or environment.

The value of this model is that it illustrates how the cognitive demands involved in motor performance may change as practice continues. However, the model does not by itself explain why some individuals improve more quickly than others. This raises the question of whether individual differences in cognitive abilities may contribute to the process of motor learning.

It is important to consider that cognitive abilities and motor learning may also hold a bidirectional relationship. Findings from a recent review indicate that cognitive abilities may support motor-skill acquisition, while engagement in motor learning may also provide opportunities to exercise cognitive processes such as working memory, inhibition, and cognitive flexibility (Bao et al., 2024). Thus, motor-skill training may also function as activities through which cognitive processes may be exercised. This relationship makes causal interpretation difficult in studies that assess cognition and motor performance at a single point in time. Previous motor experience may contribute to cognitive development, while cognitive abilities may also affect subsequent motor learning.

### **Working Memory and Motor Learning**

Although intelligence is often represented using a single score, contemporary theories conceptualize cognitive ability as multidimensional. The Cattell-Horn-Carroll framework, for example, includes broad abilities such as fluid reasoning, crystallized knowledge, working memory, processing speed, visual processing, and long-term retrieval (Schneider, 2018). Rather than assuming that overall intelligence equally influences all forms of learning, it may therefore be more useful to identify which specific cognitive abilities are relevant to motor skill acquisition.

Working memory refers to the ability to temporarily store and actively manipulate information while performing a task (Baddeley, 2012). It may be particularly relevant during motor learning because learners may need to consciously process instructions, remember

movement sequences, monitor errors, and compare their performance with the intended movement. Working memory may therefore support the temporary maintenance and manipulation of information required while acquiring an unfamiliar skill.

Several studies have identified relationships between working memory and motor learning. Empirical evidence suggests that cognitive ability, particularly working memory, contributes significantly to motor skill acquisition. For example, Kurre (2018) examined approximately 400 adolescent boys aged 12-15 using Johnson's Test of Motor Educability alongside a standard intelligence assessment. The study found a positive association between intelligence scores and motor educability, indicating that individuals with higher cognitive ability generally acquired motor skills more effectively (Kurre, 2018). However, given measurement based on a composite intelligence score, it was unclear which component of cognition was contributing to motor performance.

Previous empirical findings have also identified working memory as a particularly important predictor. Bo and Seidler (2009) found that individuals with greater visuospatial working-memory capacity learned an explicitly presented movement sequence more rapidly. Anguera et al. (2010) similarly reported a relationship between spatial working-memory capacity and visuomotor adaptation, with the relationship particularly apparent during early learning.

Comparable findings have also been reported in children. Buszard et al. (2017) found that children aged 8-10 with higher working-memory capacity showed greater improvement while learning a basketball-shooting task, particularly when they were required to follow multiple movement instructions simultaneously. Supporting this pattern, Skalaban et al. (2022) reviewed evidence across multiple motor learning paradigms and concluded that working memory, especially visuospatial working memory, consistently predicts the rate of motor skills acquisition, with its influence being most pronounced during the early stages of learning before skills become automated (Skalaban et al., 2022). Recurring results suggest a structural role of working memory in learning.

However, not all evidence supports a consistent role for working memory across motor learning contexts. Maxwell et al. (2003) investigated the role of working memory in procedural motor learning and found that procedural learning could occur without depending entirely on working-memory-mediated declarative learning. Their findings suggest that working memory may be more important for consciously controlled or strategy-based learning than for procedural learning itself. Meissner et al. (2016) similarly examined working memory in implicit motor-sequence learning and reported limited or inconsistent involvement of working memory.

Taken together, these findings suggest that working memory may contribute to motor learning under some conditions rather than acting as a universal predictor. In particular, its contribution may depend on whether the task requires learners to consciously maintain and use instructions or sequence information. The variation across these findings also raises questions about whether different forms of working memory have the same relevance to motor learning.

### **Working Memory Modality**

An additional consideration concerns the specific modality of working memory measured across studies. Working memory is not a unitary construct; contemporary models distinguish between verbal working memory, which supports the temporary maintenance and manipulation of phonological information, and visuospatial working memory, which supports the retention of spatial locations and visual patterns (Baddeley, 2012). This distinction may be particularly consequential for motor learning research, given that the literature linking working memory to

motor sequence acquisition has predominantly implicated the visuospatial rather than the verbal component.

The modality selected to assess working memory may affect whether an association with motor learning is detected. For example, Bo and Seidler (2009) found that visuospatial working memory predicted the rate of explicit motor sequence learning. Subsequent work by Bo et al. (2011, 2012) similarly reported that visuospatial working memory was more consistently related to sequence learning performance than verbal working memory across both implicit and explicit tasks. It has further been proposed that motor working memory may itself represent a subset of the visuospatial system rather than the verbal one, given the shared reliance on spatial and kinaesthetic coding of movement information (Wu & Coulson, 2015). Future studies could therefore examine verbal and visuospatial working memory within the same motor-learning task to determine whether this correspondence contributes to differences across findings.

### **Processing Speed and Motor Learning**

Processing speed refers to the speed at which an individual can perceive, interpret, and respond to information accurately (Anderson et al., 2021). During motor performance, faster processing may theoretically allow individuals to interpret task-relevant information and respond to feedback more efficiently. This could help learners identify errors and adjust their movements during repeated practice.

Evidence from repeated practice sessions of a certain skill may indicate a positive relationship between processing speed and motor learning. For example, Ackerman and Beier (2007) found that perceptual-speed measures predicted better performance across skill-learning tasks involving several hours of practice. However, these studies primarily involved complex cognitive-psychomotor tasks rather than isolated motor-sequence learning, limiting generalisation to motor acquisition. More recent evidence also suggests that processing speed may not predict all forms of motor learning; Han et al. (2025) found that although participants differed consistently in processing speed, faster processing speed was not associated with better implicit motor-sequence learning. Inconclusive evidence points to gaps that need to be addressed by further investigations.

In contrast with working memory, the role of processing speed in motor-learning rate is less clearly established in the literature. Chiaravalloti et al. (2013) found that processing speed was more strongly associated with new learning than working memory, suggesting that the two cognitive abilities may contribute differently to learning. Taken together, current evidence suggests that processing speed may represent a theoretically plausible, but comparatively underexplored contributor to motor learning. Importantly, its contribution may not be constant across practice. Determining whether this relationship varies across stages and types of motor learning therefore remains an important question.

### **Why Findings Across Studies May Differ**

In light of evidence pointing to cognitive ability as a predictor to motor skill acquisition, some studies complicate the picture as they offer new perspectives on the claim. Maxwell et al. (2003) investigated the role of working memory in motor skill acquisition across three experiments by manipulating participants' access to visual and auditory feedback about the outcome of their movements. Their findings indicated that procedural knowledge could develop even when opportunities to consciously evaluate performance and form declarative knowledge were restricted. This suggests that some forms of motor learning may proceed without strong

reliance on working-memory-dependent knowledge. Importantly, their findings also challenge the traditional assumption that motor skills must first be consciously learned through declarative processes before becoming procedural and automatic.

On the other hand, findings from implicit motor-sequence learning also complicate the proposed relationship between working memory and motor learning. Meissner et al. (2016) examined the relationship between working memory and implicit motor sequence learning in adults aged 18-71. Using an implicit sequence learning task, they found that working memory showed some involvement in motor sequence learning, but this relationship was limited and inconsistent. This suggests that although working memory may contribute to certain aspects of motor learning, it is not consistently required for implicit procedural learning. This finding challenges the assumption that individuals with greater cognitive abilities will necessarily learn a new procedural motor task faster, as cognitive ability may not provide a consistent advantage when learning occurs implicitly.

Differences in the type of motor-learning task may also contribute to inconsistent findings across studies. Research on motor learning has used a wide range of paradigms, including sequence-learning tasks, visuomotor adaptation tasks, and applied motor skills. Ranganathan et al. (2022) noted substantial variation in the motor tasks used across studies of individual differences in motor learning, with much of the literature concentrated on adaptation and sequence-learning paradigms. These tasks may place different demands on the learner. For example, sequence-learning tasks require participants to acquire an ordered pattern of responses, while visuomotor adaptation requires adjustment of movement in response to altered sensory feedback. Research on sport skill acquisition also involves more complex and context-dependent performance demands (Choo et al., 2024). Because these tasks do not assess identical forms of motor learning, the same cognitive ability may show different relationships with performance across task types. Findings from one motor-learning paradigm should therefore be generalized to another with caution.

Similarly, variation in the measurement of motor learning may further contribute to inconsistent results. Motor learning has been assessed using a range of outcomes, and the definition of successful learning differs between studies. Anderson et al. (2021), in their systematic review of individual differences in motor skill learning, emphasized that individuals can differ in their performance during practice and in how they respond to different practice conditions. Measures of acquisition examine changes that occur during practice, while retention and transfer tests assess whether learning is maintained or applied under different conditions. Ranganathan et al. (2022) further identified substantial methodological variation in research investigating individual differences in motor learning. Their critical review found considerable variation in the outcomes used to represent learning and in the time over which learning was assessed. This variation means that studies described as investigating “motor learning” may not necessarily measure the same aspect of learning. A study measuring improvement during practice may therefore produce different findings from another measuring retention after delay.

The relationship between working memory and motor learning may also vary according to practice conditions. Lage et al. (2024) specifically examined the interaction between working memory capacity and practice schedule. Participants were assigned to constant or random practice while learning a sequential key-pressing task, followed by delayed retention and transfer tests. Working-memory capacity was associated with transfer performance differently across the two practice schedules. Within constant practice, participants with higher working-memory capacity showed better transfer performance, whereas this difference was not

observed in the random-practice condition. Lage et al. (2024) interpreted these findings as indicating that the contribution of working-memory capacity may depend on the cognitive demands created by the practice schedule.

Overall, variation across studies may partly reflect differences in what learners are asked to do and in how learning is assessed. These factors should be considered when interpreting the strength of the relationship between cognitive abilities and motor learning.

### **Future Directions to Support Motor Learning in Adolescents**

Most existing research on the relationship between cognitive ability and motor learning has focused on children or adults, with adolescents being relatively underrepresented. Studies such as those by Wang and Wang (2024) and Ghorbanzadeh et al. (2025) primarily examine younger children, while many laboratory studies use adult samples. This limits the generalisability of existing findings to adolescents.

Future research with adolescents should examine whether the modality of working memory affects its relationship with motor learning. Studies could assess verbal and visuospatial working memory within the same sample and relate each measure to the same motor-learning task. This would help determine whether stronger associations with visuospatial working memory reflect a closer match between the cognitive measure and the demands of the motor task.

Future studies should also examine motor learning beyond improvement during practice. Including delayed retention or transfer tests would help determine whether a cognitive ability associated with rapid acquisition is also associated with learning that persists after practice ends. This distinction is important because acquisition and later retention may reflect different aspects of skill learning.

Practice conditions should also be examined experimentally. The findings of Lage et al. (2024) suggest that the relationship between working-memory capacity and performance can change according to the practice schedule. Future studies could compare practice conditions within the same sample to determine whether cognitive abilities become more relevant under particular learning demands.

Processing speed requires more direct investigation in motor-learning research. Existing findings provide limited evidence concerning its relationship with motor-learning rate. Studies designed specifically to assess processing speed alongside repeated measures of motor performance would help clarify whether it contributes to acquisition and whether its relevance changes across the course of practice.

Research focused specifically on adolescents would provide a stronger basis for determining whether relationships observed in children and adults also apply during adolescence. This would improve the developmental relevance of findings and provide clearer evidence for educational and rehabilitation contexts.

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