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Review

Understanding and Assessing the Interconnectedness of Motor and Cognitive Development: A Novel View on Complexity in Dual-Task Paradigms

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Abstract: Human development encompasses the integration of neuromotor, psychological, social-emotional, and cognitive processes across time. This paper seeks to advance the understanding of motor and cognitive development by proposing a novel assessment paradigm. Specifically, we aim to 1) provide a conceptual bridge, based on multidisciplinary evidence, to effectively link the concurrent development of motor competence and executive functions via learning-related and exercise-related neurotrophic mechanisms, and 2) use this conceptual bridge to inform the development of novel motor-cognitive dual-task assessments that account for the role of movement task complexity, current levels of motor competence, and the continuous decision-making inherent in real-world performance environments. Traditional assessments of motor competence have focused on skillfulness using restrictive protocols that decontextualize performance and limit cognitive involvement, while motor-cognitive dual-task assessments have minimized the impacts of movement task complexity and motor competence on cognitive performance. In contrast, our approach enhances the sensitivity of motor-cognitive assessments to individual differences while enabling a more nuanced exploration of the concurrent development of motor and cognitive systems, offering valuable insights for both research and applied settings.

Keywords: executive function; perception-action; dual-task; motor competence; motor development; measurement

1. Introduction

The development of motor competence (MC) is foundational for individuals to perceive, explore, and interact with their physical environment, potentially serving as a vital precursor for advancements in cognitive, psychological, social, and emotional development across the lifespan [1,2]. MC, defined as the neuromuscular coordination and control required for effectively engaging in a wide range of movement goals, enables individuals to effectively explore, perceive, and engage within dynamic, task-specific contexts [3]. From an embodied cognitive perspective, the acquisition of a robust foundation in diverse movement patterns (i.e., MC) extends beyond physical development, intricately intertwining with cognitive processes by facilitating the exploration of novel and challenging physical and perceptual states [4]. Likewise, core executive functions (EFs) are indispensably involved in the complex and continuous processes of decision-making and behavior regulation, which promote exploration in real-world environments. EFs are typically conceptualized as top-down cognitive processes that enable individuals to regulate volitional behavior and effectively align their actions with their task-goals [5]. To more effectively understand the concurrent development of MC and EFs, it is essential to recognize that both processes unfold through a coupled,

dynamic system of perception and action. Within this system, motor-cognitive solutions are not pre-determined but emerge in real time as individuals continuously adapt to environmental and task-specific constraints alongside their own developing capabilities [6,7]. Through this lens, the reciprocal relationship between motor and cognitive processes becomes essential in understanding how individuals adapt and thrive in complex and dynamic environments.

Despite well-established links between MC and cognitive processes [8–13], existing MC assessments predominantly emphasize physical skillfulness, often employing isolated and decontextualized task protocols that fail to capture the complexity of motor-cognitive interactions [14]. Traditional motor-cognitive dual-task (DT) assessments, by focusing on the application of extrinsic cognitive demands, frequently overlook the impacts of movement task complexity and previously developed levels of MC on cognitive performance. These approaches are inherently limited in their capacity to capture the nuances of the concurrent development of MC and EFs across the lifespan.

This theory-based conceptual paper aims to address these limitations by proposing an integrated assessment paradigm that reflects the ecological validity and complexity of real-world task environments. Specifically, we aim to 1) provide a conceptual bridge, grounded in multidisciplinary evidence, to effectively link the concurrent development of MC and EFs via learning-related and exercise-related neurotrophic mechanisms, and 2) use this conceptual bridge to guide the development of novel motor-cognitive DT assessments that account for movement task complexity, current levels of MC, and continuous decision-making processes. Unlike traditional dual-task paradigms, which often rely on decontextualized tasks and fail to capture the dynamic nature of motor-cognitive interactions, our approach emphasizes the real-time emergence of motor-cognitive solutions within ecologically valid, complex environments. By adopting a framework grounded in ecological dynamics and embodied cognition, we aim to enhance the sensitivity of motor-cognitive assessments, providing deeper insights into individual differences and fostering a more comprehensive understanding of the concurrent development of motor and cognitive systems. This novel paradigm not only addresses gaps in existing methodologies but also holds significant potential to inform interventions across educational, clinical, and applied research settings.

1.1. Executive Functions and Their Development

EFs are employed ubiquitously to facilitate or inhibit behaviors, transition between tasks, and modify behavioral strategies to meet contextual demands [15,16]. The developmental trajectories of EFs extend well into adulthood, characterized by a prolonged maturation phase and an age-related decline, which parallels the extended development and early-onset aging of the prefrontal cortex—a critical, though not exclusive, neural substrate of EFs [17,18]. Within this developmental trajectory, evidence highlights sensitive periods in early childhood [19,20] and adolescence [21], where heightened neural plasticity and an increased responsiveness to environmental stimuli present unique opportunities for cognitive and neural growth. Despite these insights, our understanding of EF development across the lifespan remains limited by the absence of a unified conceptual framework that captures the complexities of EFs during both development and aging.

A three-factor model of EF is frequently cited in the literature [22]. This model identifies three foundational EF constructs: (1) Inhibitory Control – the capacity to suppress distracting stimuli or override automatic responses to execute a task-relevant action, (2) Working Memory – the active updating of irrelevant information with pertinent task-related information to enable goal-oriented behaviors, and (3) Cognitive Flexibility – the capability to shift between task demands or response rules [22]. The number and nature of EF constructs in different models appear to vary across developmental stages [17]. Karr and colleagues [23] provide evidence suggesting that in early childhood, EF may manifest as a one- or two-dimensional construct (excluding cognitive flexibility), with a gradual increase in multidimensionality as development progresses. The three-factor model becomes more prevalent in school-aged children, adolescents, and adults, reflecting the progressive differentiation of EFs over time. Cognitive flexibility emerges during school age, suggesting that the

core EFs neither “come online” at the same time, nor develop at the same rate. This progression from unity to diversity of EF constructs has led to the proposal of developmental sequences, wherein certain EFs may facilitate the development of others. For example, cognitive flexibility may not fully develop until a threshold level of inhibitory control and working memory, which have earlier developmental trajectories, is reached [17]. These three core EFs, in turn, are considered the basis of higher-level EFs such as problem-solving, reasoning, and planning [5].

While the factorial structure of the umbrella construct of EF is still an issue of research and debate [23], there is a range of non-core EFs that are conceptually addressed, assessed, and reviewed beyond the three-factor model [24]. Recent classifications have expanded the conceptualization and assessment of EFs beyond a purely “cognitive” framework. Within cognitive psychology, EFs are typically evaluated in “cool” contexts, which are characterized by minimal incentives and/or low emotional intensity. For example, a child might advise a peer to stay focused on a task and delay gratification to receive a larger reward upon completion (a “cool” EF scenario, requiring reasoning and planning in an emotionally neutral context). However, the same child might struggle to apply this advice to their own behavior when directly confronted with the choice between an immediate, smaller reward and a delayed, larger reward (a ‘hot’ EF scenario, requiring the regulation of emotional and motivational impulses). The key distinction lies in how cognitive control processes adapt to situational demands that require the management of emotion and the modulation of motivation, particularly in emotionally salient contexts involving approach or avoidance behaviors [25]. Given that EFs govern volitional behavior, their application extends across a continuum of affective and motivational domains that cannot be driven by purely cognitive processes. Thus, a distinction of “cool” and “hot” EFs have been proposed [26–28], with the first being assessed in a decontextualized and affectively neutral manner, and the latter being assessed in contexts where the emotional-motivational aspects of behavior are more salient. The three most investigated foundational EFs belong to “cool” EFs, as they have been mostly assessed with tests that do not involve affectively laden decisions.

Like other EF models, the “cool-hot” distinction has been studied from a developmental perspective, suggesting divergent developmental trajectories. Specifically, “hot” EFs appear to mature later than “cool” EFs, which develop earlier in childhood [26,28]. This differential progression, which emerges in early childhood and continues through adolescence, is often cited as supporting the construct validity of these categories [29,30]. In preschool-aged children, research indicates that “cool” EFs are linked to academic performance, while “hot” EFs correlate more closely with disruptive and social problem behaviors [29,31]. However, contrasting evidence challenges this distinction, particularly when affective salience is the only distinguishing factor between “cool” and “hot” EF assessments [32]. Thus, the issues of conceptualization are intertwined with those of assessment and contextualization.

We consider the “cool-hot” distinction particularly well-suited for the context of motor-cognitive developmental research and the specific aims of this theory-based conceptual paper, which advocates for a more contextualized understanding and assessment of cognitive development as it relates to motor behavior. Firstly, this model is not dichotomous but rather spectrum-like, where the context determines whether and to what extent an EF is “cool” or “hot” [33]. Secondly, the “cool-hot” EF model integrates both cognition and emotion, as well as their associated neural substrates, both of which are integral to motor learning and performance [34,35]. Overall, EFs work synergistically with the acquisition and sustained development of MC across the lifespan [9]. Intriguingly, the role of “hot” EFs in motor behavior becomes more evident in neurodevelopmental disorders characterized by impairments in motor coordination and EFs. For example, in children with Developmental Coordination Disorder, EF deficits are not limited to “cool” EFs, as action planning, execution, and coordinative control can be hindered by low inhibitory control in emotionally laden situations [36]. As a result, the linkage between MC and both “cool” and “hot” EFs is drawing increased attention from motor developmentalists, developmental neuroscientists, and kinesiologists [8].

1.2. “Cool” and “Hot” Executive Functions and a “Cool-Hot” Gradient

Traditionally, “cool” cognitive paradigms have emphasized the cultivation and preservation of cognitive processes that subserve goal-oriented and prospective behaviors within decontextualized, analytically reductive, and affectively neutral experimental contexts [22,28]. The emphasis on “cool” cognition is rooted in clinical brain neurophysiology and cognitive psychology [28]. On the one hand, pioneering clinical research on focal brain damage revealed distinct behavioral outcomes between frontal and posterior cortical lesions, with frontal patients exhibiting marked deficits in their capacity to adapt fundamental cognitive processes to emergent task demands [37,38]. Subsequent research, influenced by the dominating mentalistic approach of cognitivism and the organic approach of cognitive neurosciences, was consequently focused on “cool” EFs, emphasizing the relation between frontal lobe structures and goal-directed behaviors fundamental to adaptive functioning [39]. Specifically, investigators delineated prefrontal cortex-mediated cognitive processes and identified neural networks implicated in cognitive control [40]. Lesions to the prefrontal cortex, may not significantly compromise EF performance in isolated contexts but could manifest in deficits in poor social regulation and heightened impulsivity within social contexts [41,42]. The identification of frontal regions subserving socio-emotional regulation [43] is paralleled, at the behavioral research level, by a burgeoning interest in the contextualized application of EFs within the affective and motivational domains of risk-reward assessment and decision-making, now commonly termed “hot” EFs [26].

Emotional stimuli have a significant impact on cognitive performance [44]. Thus, the capacity to selectively attend to pertinent environmental stimuli while concurrently suppressing emotionally charged distractors and competing response options is paramount for behavior regulation and achieving task-goals [45,46]. “Hot” EFs play a critical role in filtering out emotionally irrelevant information via emotional gating mechanisms. As representations of task-sets, goals, and other pertinent information are dynamically updated, these emotional gating mechanisms serve to optimize the capacity of working memory [46,47]. Individuals frequently employ “hot” EFs to adaptively modulate emotion regulation strategies in response to situational demands [48]. Specifically, “hot” EFs are recruited within social contexts to self-regulate responses to stimuli such as reward processing, social cues, and affective decision-making, thereby facilitating successful interpersonal interactions [49]. The modulation of “hot” EFs is linked to neural activity within two distinct regions in the frontal lobe of the brain [50] that facilitate the regulation of limbic processes under conditions of heightened emotional and motivational salience [27,51–53].

While dichotomizing EFs into “cool” or “hot” processes offers valuable insights into discrete behavioral components, this reductionist framework overlooks the interconnectedness and integration of EFs within real-world contexts [20]. Given the complex and interdependent nature of neural network activity, the delineation between cognitive and emotional processes remains contested, as cognition inherently encompasses both rational and affective information [44,54,55]. Zelazo and Müller [27] proposed a continuum model of “cool” and “hot” EFs, positing “cool” and “hot” processes as polar ends with individuals concurrently engaging both “cool” and “hot” EFs at varying proportions based on situational demands, analogous to tempering water to attain a desired temperature. This tempering of “cool” and “hot” EFs facilitates exploration and meaningful interaction with an individual’s environment. Brain electrophysiological evidence suggests that the anterior cingulate cortex may have the role of a true nexus of emotional and cognitive processing involved in “cool” and “hot” EFs [56].

Neuroimaging and psychophysiological evidence further support the “cool-hot” EF gradient hypothesis, as traditionally “cool” cognitive tasks elicit activity in cortical areas which are commonly associated with emotions, suggesting functional relations between “cool” and “hot” brain regions [57,58]. In addition, the central autonomic system is functionally coupled with cognitive and emotional processing, as its neural network crosses all local networks that subserve both “cool” and “hot” EFs [59]. Moreover, Achievement Goal Theory in motivational psychology offers a cognitive-motivational perspective by integrating emotional and social cognitive processes, emphasizing that

goal-directed behaviors are influenced by emotional and motivational states. (e.g., [60]). Therefore, tasks investigating “cool” EFs cannot be devoid of “hot” EFs as motivation and emotion are ever-present in goal-directed behaviors; thus, providing further empirical support towards the “cool-hot” EF gradient hypothesis.

2. How May Motor Learning Promote Executive Function Development?

In the previous section, we explored the interconnectedness of cognitive and emotional processes and their neural substrates within the framework of “cool” and “hot” EFs. Now, extend this discussion by incorporating motor processes into the picture [61]. Moving beyond a purely mentalistic view of cognition, proponents of embodied cognition argue that cognition is grounded in perceptual, emotional, and sensorimotor processes [1]. Advances in neuroscience are redefining traditional notions of the siloed involvement of neural circuitries in either cognitive or motor functions in favor of their joint involvement in both. The cerebellum and basal ganglia, once considered exclusively motor structures, are now recognized for their roles in supporting EFs and emotional regulation by interacting with the prefrontal cortex [62–64]. Given these insights, the “cool-hot” EF framework is particularly relevant for understanding how EFs interact with sensorimotor processes in motor skill learning, which demands cognitive effort and typically occurs in emotionally laden and motivationally salient contexts [65].

A promising avenue of inquiry is to examine the influence of motor learning processes on the development of EFs. The human brain dynamically adapts both functionally, by adjusting patterns, strength, or efficiency of neural activity, and structurally, through anatomic changes by creating new synapses and generating new neurons to meet environmental demands. For instance, the initial acquisition of movement coordination and control emerges through functional neural adaptations, which can lead to significant improvements in physical performance within a single training session [66,67]. With continued motor skill practice, structural changes occur over time within the regions of the brain that are activated during motor skill acquisition and performance [66,68]. These structural changes involve the creation of new synapses and new neurons, processes commonly referred to as synaptogenesis and neurogenesis, respectively [68]. The brain leverages these functional and structural connections to dynamically regulate neural processes within and across networks, adapting to the specific demands of the performer’s task-goal [69–71]. Promoting functional and structural adaptations across the brain is critical for the development of core EFs and the emergence of increasingly complex cognitive functioning across the lifespan [72]. Thus, a better understanding of the integrative and dynamic nature of motor learning and cognitive processes is needed to align MC assessments more effectively with cognitive outcomes.

2.1. Skill Acquisition and Functional Adaptations

Skill acquisition induces functional changes in neural activity within key neural networks, particularly the fronto-parietal network (linked to cognitive control) and the default mode network (linked with automaticity) [73]. These networks exhibit inverse functional activation patterns as skill levels increase, which may signal a transition from effortful cognitive control-based task execution to more automated task execution [74]. Increases in neural activity in the default mode network also signify an expansion of cognitive resources available for allocation to processes like introspection, memory retrieval, and prospective thinking which are essential for effective decision-making [74]. Conversely, the fronto-parietal network is primarily engaged in allocating attentional resources to salient task and environmental stimuli [75,76]. Thus, default mode network activity inversely correlates with task and environmental complexity [77–79]; suggesting that reduced fronto-parietal network activity may serve as a neural indicator for learning, automaticity, and decreased demands on cognitive control in movement execution.

For example, when learning a visuo-motor task, higher-level performers decrease neural activity in the fronto-parietal network and increase activity in the default mode network earlier than lower-level performers [80]. Therefore, functional shifts in neural activity from the fronto-parietal network

to the default mode network may also reflect a decrease in challenges to EFs as cognitive resources are no longer allocated to explicitly coordinate and control movement execution. Functional changes in neural activity between networks may represent some EF-related benefits of skill acquisition, as finite cognitive resources are freed with increasing levels of automaticity and skillfulness. However, motor skill complexity and skill retention also promote structural changes which serve unique roles in improving EFs, fostering their development through continual challenges imposed by enhanced task difficulty and novel environmental demands [81].

2.2. Skill Retention and Exercise-Related Structural Adaptations

Motor learning drives neuroplasticity across multiple brain regions, including the cerebellum [12,81], basal ganglia [82,83], hippocampus [84], and prefrontal cortex [12], reflecting the multidimensional nature of skill acquisition as it integrates social-emotional, psychological, cognitive, and physical domains. The acquisition stage of motor learning is characterized by functional changes in neural activity within and between neural networks [66,67]. Meanwhile, the retention stage of motor learning is primarily associated with synaptogenesis [85] and neurogenesis [86]. Evidence from rodent models demonstrates that complex skill learning promotes increases in synaptogenesis within the cerebellum, basal ganglia, and prefrontal cortex [87]. Complex skill learning also impacts memory and learning processes in rodents by promoting the development of newly generated neurons in the hippocampus [86,88]. The acquisition and retention of increasingly complex motor skills requires effortful and sustained practice over time which may promote larger synaptogenic and neurogenic effects compared to less complex motor skills [86,89]. Complex motor skill practice requires individuals to actively attend to changing task and environmental information and adapt skill performance to effectively accomplish the task-goal which may challenge EFs more than less complex tasks. Moreover, emerging evidence indicates that an individual's level of MC plays a pivotal role in shaping the neural adaptations resulting from skill learning [90]. Consequently, motor learning paradigms must strike an optimal balance between the learner's MC level and the complexity of the movement tasks to foster effective learning, sustained performance, and motivation [91], ultimately supporting EF development [92–94]. This emphasis on aligning task complexity with the learner's MC level underscores the need for advancing DT paradigms, a focus central to our framework's objective of capturing nuanced motor-cognitive interactions.

In contrast to motor learning-related effects on EF development, investigations into exercise-related mechanisms have demonstrated positive effects on both angiogenesis, which refers to the generation of new blood vessels, and neurogenesis [95]. However, recent evidence indicates that exercise intensity may moderate the magnitude of these angiogenic and neurogenic effects [96–98]. Exercises performed at moderate to vigorous intensities may stimulate angiogenesis and neurogenesis by increasing blood flow as well as energy and oxygen demands [99]. Evidence in mice further supports the moderating effects of exercise intensity on angiogenic responses as high-intensity exercise promotes greater levels of angiogenesis compared to moderate- and light-intensity exercise [98]. Similarly, neurogenic effects may be influenced by high-intensity exercise as research in humans has demonstrated more pronounced neurogenesis compared to moderate- and light-intensity exercise [96,97]. Angiogenesis, facilitated by exercise-induced hypoxia (i.e., oxygen deprived tissues), upregulates growth factors like vascular endothelial growth factor, which stimulates vascular changes necessary for neurogenesis [100,101]. These vascular adaptations are crucial because they precede neurogenesis [102], promoting new neuron survival and integration [103,104]. Because exercise promotes angiogenesis and neurogenesis, the moderating role of exercise intensity must be considered when investigating exercise-related effects on cognition. As mentioned in section 2.1, complex skill learning is deeply intertwined with cognitive development; however, evidence focusing on the interactions between movement task complexity, exercise intensity, and EF-related outcomes is limited and warrants investigation.

In summary, motor learning drives EF and cognitive development through dynamic functional adaptations and structural changes, including synaptogenesis and neurogenesis, shaped by skill

acquisition, retention, and exercise intensity. The acquisition and retention of complex motor skills require sustained, effortful practice that promotes neural plasticity and challenges EFs, particularly in environments with dynamic task and environmental demands. Critically, an individual's level of MC influences the neural adaptations resulting from motor learning, emphasizing the need for assessment paradigms that allow participants to dynamically adjust exercise intensity and task complexity to align with their MC level. By providing opportunities for learners to explore and adapt to task-specific demands within the assessment environment, these paradigms not only enhance learning and performance but also capture the nuanced and reciprocal interactions between motor and cognitive systems, offering a deeper understanding of their concurrent development across the lifespan.

3. Developmental Perspectives on Motor Competence and Executive Functions

The development of MC (i.e., neuromuscular coordination and control required for effectively engaging in a wide range of movement goals) concurrently facilitates cognitive development via learning- and exercise-related mechanisms. Learning-related mechanisms are influenced by movement task complexity while exercise-related mechanisms are influenced by the metabolic demands of physical movement [65]. A comprehensive understanding of the interconnectedness between MC and EF development necessitates an examination of the dynamic coupling between perception, action, and decision-making processes within complex and evolving environments. Effectively completing any task requires individuals to perceive and interpret the affordances present within the task-environment in reference to their own movement capabilities to establish viable opportunities for action within the environment [6,105]. Thus, movement emerges as a coupled, dynamic function of perceiving and responding to constraints inherent within the task-environment and individual [6,7], commonly referred to as perception-action cycles. For example, when catching a ball, an individual must continuously perceive the ball's trajectory, speed, and distance while adjusting their posture, hand positioning, and movement timing to successfully complete the task. Similarly, in navigating a crowded room, an individual interprets the spatial positioning and movement of others while dynamically adjusting their own path to avoid collisions. These cycles demonstrate the ongoing reciprocal interaction between perception and action, where each informs and shapes the other in real time. Embodied cognition encompasses these dynamic interactions between cognition and MC, spanning both micro- and macro-timescales, which are shaped by an individual's discovery of novel perception-action couplings through repeated and meaningful interactions with their environment [106]. Aligned with this view, the Skilled Intentionality Framework offers unique insight into "hot" EFs as these cognitive processes are intricately intertwined with bodily interactions, dynamically responsive to context-specific experiences, and linked to an individual's emotional state [107]. Furthermore, we assert that computational and representational theories of cognition offer complementary perspectives (i.e., "cool-hot" gradient) on symbolic representations, abstract reasoning, and mental imagery [108]; processes which rely on "cool" EFs to effectively facilitate the development of strategic solutions for both motor and cognitive challenges.

To enhance one's capability to control their movements and explore the environment, individuals must effectively regulate the dynamic coupling of perceptions and actions to complex tasks and environmental demands. In the early stages of motor development, learners often constrain or "freeze" degrees of freedom within the musculoskeletal system to establish stable coordinative structures and optimize control for goal-directed actions [109,110]. For instance, when infants first begin to walk independently, they often "freeze" their arms in a high-guard position to simplify the complex physical demands associated with dynamic postural control [111]. With increased practice, infants begin to explore a wider range of movement patterns by "releasing" degrees of freedom to facilitate more complex locomotor patterns, such as adding oppositional arm movements. Over time, this "releasing" will result in the emergence of a newly stable and more advanced locomotion which, in turn, will enhance the discovery of opportunities for action within the environment and provides

deeper insight into object properties and spatial relations [105,112]. The acquisition and advanced development of walking, as with the acquisition and refinement of all motor skills, necessitates the inhibition of primitive neuro-motor synergies [113], the utilization of working memory for spatial orientation and self-navigation [1], and the flexible allocation of attention between interacting with objects, toys, other children, or adults while navigating the physical environment. Thus, active exploration within the task-environment, coupled with the selective attention to task-relevant perceptual information (i.e., affordances), fosters both skill development and the development of core “cool” EFs [94]. In addition, infants may engage core “hot” EFs while initiating or regulating goal-directed behaviors, such as repeated attempts to walk despite failure, by referring to emotional signals provided by adults [114]. These cognitive processes are integrated within the sequential development of a variety of increasingly complex locomotor and object control skills, like hopping, jumping, throwing, and kicking, which advance in an intransitive and cumulative manner across childhood and adolescence.

The integration of motor skill tasks into educational programs presents educators with a valuable opportunity to foster the concurrent development of EFs and MC through ecologically valid, engaging, and developmentally appropriate activities. Structured movement-based interventions—such as obstacle courses and group games requiring coordinated movements, quick decision-making, and attentional shifts—can immerse learners in perception-action cycles that closely mirror real-world demands. These activities not only promote active exploration but also encourage learners to selectively attend to task-relevant affordances, such as navigating obstacles or synchronizing movements with peers. Similarly, incorporating short, structured physical activity breaks into classroom routines—such as combining movement with memory recall tasks or problem-solving challenges—has been shown to enhance executive functions, including working memory, attentional control, cognitive flexibility, and self-regulation [115–117]. Beyond these immediate developmental benefits, integrating motor-cognitive tasks into educational settings equips teachers and researchers with practical tools to design assessments that capture the complexity of real-world environments. By aligning assessments with the reciprocal dynamics of EF and MC, educators can more effectively tailor curriculum design and individualized learning strategies to meet the diverse needs of students.

3.1. Linking Motor Skill Learning and Motor Competence Assessment to Executive Functions

Despite the prevalent misconception of spontaneous skill acquisition (i.e., skills are developed “naturally”), the complex developmental trajectory of MC necessitates repeated, effortful, and successful interactions with perceptually rich and dynamic environments [118]. While simplified tasks and tightly controlled environments are often perceived to benefit short-term skill acquisition [119], promoting variability in task and environmental conditions is a hallmark of various motor learning and development theories as it optimizes learning and retention from a developmental perspective [3,94,120,121]. Therefore, motorically complex tasks embedded within dynamic environmental conditions, although they incur slower acquisition rates, promote higher levels of neural activity in the fronto-parietal network that underlies EFs [122,123] and the generation of new synapses in the motor cortex [85,89]. This perspective emphasizes the critical role of complex, embodied experiences in fostering the long-term development of MC and EFs [92,93].

Moreover, according to the exercise-related mechanisms introduced in section 2.2, the development of EFs is also enhanced through the physical effort and intensity generated by the prolonged and effortful practice of complex motor skills that are needed to continuously develop higher levels of competence. Specifically, engaging in structured and unstructured play, sports, or focused skill training provides opportunities for sustained moderate-to-vigorous physical activity, thereby fostering the development of cardiorespiratory and musculoskeletal fitness [124–126]. Physical activities and sports that inherently require complex skill performance also stimulate the development of musculoskeletal fitness via enhanced inter- and intra-muscular recruitment strategies [127]. Higher levels of exercise intensity are also related to more pronounced vascular and neurotrophic benefits [97] which may result in differential effects of complex skill learning for lower

and higher skilled individuals. For example, higher-skilled individuals generally have greater force production capabilities than lower-skilled individuals [124–126,128] which is associated with higher levels of energy expenditure during object projection skills like throwing and kicking [129,130].

Exceptions to the skill debate may emerge in cases involving Developmental Coordination Disorder, where the intensity and frequency of physical activity and motor skill interventions are crucial. The benefits of these interventions on physical, cognitive, and psychological outcomes are dose-dependent, with greater improvements observed with higher intensities and frequencies of physical activity [131]. Notably, EFs that are closely tied to motor activity, such as those related to behavioral regulation (e.g., working memory, self-regulation), show the strongest associations with motor difficulties and the most significant gains from targeted interventions [132]. Thus, a logical line of investigation may be to explore the potential differential effects of complex skill learning on cognitive outcomes, particularly through physiological mechanisms modulated by exercise (i.e., physical activity) intensity.

In the sections above, we have emphasized how the development of EFs is intricately interwoven with complex skill learning and the concomitant integration of motor-cognitive processes in real-world activities. For these reasons, we believe there is a need for assessments that effectively tap into the reciprocal processes of the motor and cognitive systems, as well as their individual contributions to overall motor-cognitive performance. This section introduces a novel approach to MC-EF paradigms by presenting motor tasks that concurrently require a) greater motor task complexity than traditional single- and dual-task paradigms, b) demand increased motoric and cognitive engagement, and c) closely mirror real-world scenarios, thus exhibiting greater ecological validity. Furthermore, by employing novel assessments that demonstrate developmental validity across the lifespan, we can comprehensively evaluate EFs and track the development of embodied cognition across time.

3.2. Limitations of Current Motor Competence Assessments and Their Mis/Alignment with Executive Functions

Restrictive assessment protocols in current MC assessments limit ecological validity and therefore diminish their ability to capture motor and cognitive performance [14,133]. For example, discrete MC assessments, such as the standing long jump, supine-to-stand, and throwing for speed, decontextualize the motor skill and disregard the complex and continuous nature of cognitive processes—particularly those related to EFs—inherent in embodied performance settings.

Discrete MC assessment protocols typically impose restrictive task demands which either purposefully or inadvertently limit participant decision-making and obscure the intricate, reciprocal relations between perception-action cycles. The theoretical underpinnings of discrete decision-making tasks assume that decision-making follows a stepwise, linear process [134,135]. This sequential process, summarized as a “decide then act” paradigm, involves the decision-maker initially perceiving affordances within the task-environment, subsequently choosing between predefined motor-cognitive solutions, and finally acting on their decision [136]. Sequential decision-making processes underlying traditional discrete MC assessments rely on rigid task protocols, which provide greater levels of experimental control and promote reproducible research. However, these tasks may have skewed our understanding of MC-cognition relations by creating static environments and predefined motor-cognitive solutions. This limitation is exemplified when researchers instruct participants to adhere to a predefined (i.e., “correct”) coordination pattern to achieve the highest possible velocity when kicking a ball in a controlled setting—where the time and accuracy constraints inherent in real-world scenarios are severely minimized or even eliminated. Such an approach fails to capture the dynamic and adaptive nature of skilled movement, where individuals must adjust their actions in response to changing task and environmental demands.

In contrast to the rigid structure of discrete assessments, continuous decision-making tasks offer a more ecologically valid alternative that captures the interconnected nature of motor and cognitive processes. Continuous decision-making is characterized by two reciprocal processes: “acting while deciding” and “deciding while acting” [136]. When “acting while deciding,” individuals initiate

motor-cognitive responses before making a definitive decision, allowing them to capitalize on fleeting opportunities. For instance, a soccer player dribbling toward the goal must scan for teammates while simultaneously deciding whether to pass or shoot based on the evolving position of defenders. Similarly, a tennis player moves toward an incoming ball before fully committing to a forehand or backhand shot, enabling them to adjust to their opponent's movements [137]. Conversely, “deciding while acting” involves real-time adaptation to emergent affordances, novel sensory information, or revised intentionality [138]. Thus, decision-making in embodied performance settings is not merely a matter of automated, heuristic responses to environmental stimuli, but rather an intricate interplay of proactive and reactive control. This dynamic process requires individuals to flexibly switch between actions, hold and manipulate information in working memory to compare past experiences with ongoing contexts, and inhibit misleading cues or habitual responses, ultimately enabling the emergence of adaptive and divergent solutions. Further, motor skill performance and adjustment capabilities are impacted by an individual's motor skill repertoire and the subsequent cognitive demands—particularly those related to executive functions—experienced by the individual during continuous decision-making tasks [139].

Building on this understanding, current MC assessments can integrate continuous decision-making by promoting time-constrained tasks that require repeated performance of discrete motor skills or the performance of continuous motor skills in more dynamic environments. Such tasks present an ever-changing landscape of motor-cognitive solutions, uniquely influenced by the individual's recent motor-cognitive responses and subject to the ongoing reciprocity of action and perception across time [140]. These dynamic tasks afford a multidimensional landscape where motor-cognitive solutions are not predefined by rigid task protocols or researcher involvement but instead emerge as individuals fluidly navigate their environment. For example, to enhance the traditional kicking task mentioned above, a simple modification such as continuously kicking and receiving a ball from a wall with a time constraint encourages individuals to explore and adapt motor-cognitive solutions. This dynamic scenario better reflects real-world performance demands, fostering adaptability, cognitive flexibility, and responsiveness to changing environmental conditions.

3.3. Integration of Executive Functions and Motor Tasks: Dual-Task Paradigms

Motor-cognitive DT paradigms provide an excellent “jumping off point” for our reconceptualization of motor-cognitive assessment paradigms, as there is a need to more effectively a) concurrently capture cognitive demands inherent within motor skills across diverse task-environments, b) offer a vast and dynamic landscape of potential motor-cognitive solutions, c) account for differences in skill levels, and d) represent dynamic real-world contexts [141].

Traditional motor-cognitive DT paradigms primarily focus on the discrete allocation of attentional resources between independent motor and cognitive tasks such as simultaneously walking and counting [142]. Although widely used, these traditional paradigms produce decontextualized tasks that are loosely and artificially linked to the perception-action cycles integral to real-world motor behaviors [143]. This limitation is particularly evident in aging research, where daily-living walking performance is often more challenging and less proficient than DT walking assessed in laboratory settings. Consequently, decontextualized laboratory testing may fail to reliably capture real-world capabilities [144]. Originally advocated in aging research [145], the ecological approach to motor-cognitive DT assessment has since been extended to examine how athletes navigate DTs that mirror the dynamic and context-specific demands of their sports [146].

In this section, we address the limited motor-cognitive DT research in children and adolescents [142], emphasizing the need for developmentally appropriate MC-EF paradigms that effectively capture the fluid, reciprocal interactions among cognition, perception, and action. Research on motor-cognitive DT abilities in children and adolescents reveals considerable variability, which likely stems from varying levels of overall EF engagement and the specific types of EFs recruited [147,148]. Understanding age-related changes in children's motor-cognitive DT performance requires careful consideration of the interconnected developmental trajectories of motor and cognitive systems. While

these developmental trajectories are intricately linked [12], motor and cognitive systems develop across distinctly different timelines. Movement skill acquisition is extensive across infancy and early childhood, as individuals develop a foundation of fundamental motor skills. This progression continues throughout childhood and adolescence, transitioning from fundamental skills to increasingly specialized and complex skills [149]. Similarly, cognitive development spans a prolonged period, with EFs exhibiting nonlinear growth characterized by a steeper developmental trajectory during the preschool years compared to kindergarten [150], and continued development into young adulthood [151]. Furthermore, core EFs develop at varying rates, with inhibition emerging first, followed by the progressive development of working memory and cognitive flexibility [17]. This developmental sequence may partially explain why DT research shows that the three core EFs both uniquely influence and are influenced by concurrent motor-cognitive walking tasks during childhood. Reciprocal DT costs—evaluated through the extent to which motor performance worsens due to the performance of a simultaneous cognitive task, and vice versa—indicate that younger children exhibit a general difficulty in managing DT walking [147]. Notably, age emerged as a significant factor influencing DT performance, particularly in tasks requiring working memory and cognitive flexibility, whereas inhibition showed no significant relationship with DT performance in these contexts [148].

The role of higher-level cognition (i.e., EFs) in locomotor-cognitive dual-tasking is well-documented in children [152], becoming even more pronounced in those affected by Developmental Coordination Disorder, who experience heightened DT interference under more complex and resource-demanding conditions [153]. Investigations of motor-cognitive DT research in children, while commendable in their efforts to examine the specific roles of EFs and task complexity, often employ DT paradigms that pair motor tasks (primarily walking) with EF tasks that inadequately represent how children naturally engage their EFs in real-world contexts. Recent efforts aim to address this limitation by leveraging augmented reality, which integrates real-world and computer-generated data to dynamically present visual content while individuals navigate outdoor environments [154]. Augmented reality undoubtedly enhances the ecological validity of DT walking paradigms; however, its current applications may lack the sensitivity needed to discriminate motor-cognitive DT abilities between typically developing children and those with Developmental Coordination Disorder, who exhibit deficits in both predictive motor and cognitive control [155]. While these motor-cognitive DTs offer greater ecological validity compared to traditional laboratory research, they likely lack the necessary complexity to fully capture the multifaceted nature of MC. Furthermore, their focus on walking-based assessments limits their capacity to represent the broader construct of MC and its intricate interactions with cognitive processes.

When exploring motor-cognitive DT tasks beyond traditional walking paradigms, as applied to children, the limitations of conventional approaches are exemplified by tools like the cognitive version of the Canadian Agility and Movement Skill Assessment (CAMSA), a widely used measure of physical literacy. In the cognitive CAMSA, participants are required to complete predefined motor-cognitive tasks such as jumping into color-specific hoops or solving basic arithmetic before throwing a ball [156]. While these tasks incorporate cognitive components, their ecological validity is limited, restricting their ability to fully capture the reciprocal dynamics between motor and cognitive processes in motor-cognitive performance. Specifically, the imposed cognitive demands are extrinsic (i.e., artificially added) to the motor tasks, failing to reflect the inherent integration of motor and cognitive processes. Moreover, the rigidly defined motor solutions constrain participants' ability to explore, adapt, and discover diverse motor-cognitive solutions, limiting the cognitive CAMSA's alignment with real-world motor-cognitive dynamics. Herold et al. [157] eloquently highlight this issue of ecological validity by distinguishing between cognitive tasks that are extraneous to completing motor-cognitive DTs (e.g., counting while cycling) and those that are integral to task completion (e.g., recalling an observed movement in a delayed imitation task of a dance sequence). This distinction underscores the importance of aligning cognitive demands with real-world motor-cognitive dynamics to better capture the reciprocal interactions of these domains. This concern has

also been highlighted in research applying motor-cognitive DT paradigms within ecological learning contexts for children, particularly with a focus on learning outcomes. The absence of integration between motor and cognitive tasks can hinder the effectiveness of motor-based learning [158], as it fails to reflect the interdependent nature of these processes in real-world contexts. Lastly, successful DT performance hinges not only on the level of integration between motor and cognitive tasks (i.e., how essential the cognitive task is to the motor task) but also on the precise timing of physical movements and the nature of the information being processed. Together, these factors significantly influence the effectiveness of DT performance and associated learning outcomes [159].

The limitations of artificially adding a cognitive task to a motor task thwart the ability of assessments to generate meaningful data capable of supporting predictive analytics in discerning individual differences in motor-cognitive capabilities, particularly those tied to skill levels and varied motor repertoires. This challenge is further underscored by a recent meta-analysis of motor-cognitive DT paradigms, which advocates for the development ecologically valid tasks that can be systematically varied across parametric dimensions [160]. As illustrated in **Figure 1**, novel paradigms offer expanded potential for assessing motor-cognitive integration by enhancing ecological validity, thereby overcoming the limitations inherent in traditional approaches.

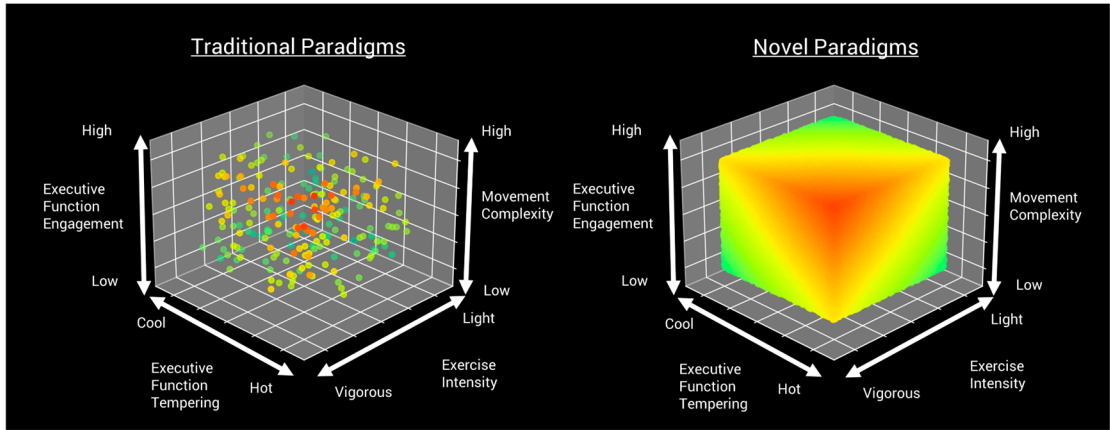


Figure 1. Comparative Models of Motor-Cognitive Solution Landscapes: Traditional vs. Novel Assessment Paradigms.

A novel and more ecologically valid approach to examining an individual’s cognitive function includes dynamic task-environments that afford a rich spectrum of motor-cognitive solutions, promoting adaptive decision-making and emergent motor-cognitive strategies within the complexities of situated action spaces. Such tasks demand greater cognitive resources to be allocated to core EFs to facilitate ongoing motor-cognitive strategies, including the integration of sensory feedback, inhibition of suboptimal motor responses, and flexible allocation of attentional resources between perceptual and motor processes. This assessment paradigm emphasizes the significance of real-time decision-making and a diverse motor repertoire within ecologically constrained action spaces. As individual, task, and environmental constraints define the action space within which motor-cognitive solutions can emerge, a diverse MC repertoire facilitates a broad spectrum of potential motor-cognitive solutions to achieve the task-goal. Figure 1 provides a conceptual representation of the dynamic landscape of potential motor-cognitive solutions, illustrating how emergent motor-cognitive solutions coalesce movement complexity, exercise intensity, EF engagement, and the tempering of “cool-hot” EF processes. As illustrated in Figure 1, novel paradigms offer an enhanced potential for assessing motor-cognitive performance by increasing ecological validity, thereby overcoming the limitations inherent in traditional approaches. Unlike traditional paradigms, which rely on predefined motor-cognitive solutions, novel approaches allow participants to explore, discover, and refine a broad spectrum of motor-cognitive solutions across the full multidimensional landscape, represented by individual data points along the figure’s axes. The color gradients in Figure 1 represent these multidimensional combinations, with warmer hues (i.e.,

orange-red) denoting motor-cognitive solutions characterized by higher movement complexity, vigorous exercise intensity, heightened EF engagement, and “hot” EF tempering. In contrast, cooler hues (i.e., light blue-green) indicate solutions with lower movement complexity, light exercise-intensity, lower EF engagement, and “cool” EF tempering. Notably, these dimensions are not static but dynamically interact to shape the potentiality for action, contingent upon the current task and environmental constraints. Moreover, as individuals engage in dynamic tasks that afford opportunities to express MC via complex movements, relative to their current motor repertoire, they will engage higher levels of EFs to effectively achieve task-goals (see section 2).

Hulteen and colleagues [14] advocate for a paradigm shift towards dynamic, ecologically constrained assessments by promoting the throw-catch [161] and supine-to-stand-and-go as exemplars of tasks that capture the dynamic interactions between perception, action, and cognition. These tasks are not merely movement tasks but represent complex, context-dependent activities where motor and cognitive processes are inherent to the task rather than extrinsic, more closely reflecting the natural integration of motor and cognitive domains.

The throw-catch task serves as a quintessential example of the perception-action cycle, where the individual is required to engage in a continuous loop of ballistic force production, object reception, perceptual monitoring, and strategic adjustments. Initially, the task demands the generation of sufficient force to project the ball into motion, an action rooted in the individual’s motor repertoire and the contextual demands of the task. As the ball travels, the performer must dynamically perceive its trajectory and velocity while rapidly integrating this perceptual information to recalibrate their body position in anticipation of the catch. This process demonstrates both “acting while deciding” and “deciding while acting,” as the individual begins motor actions before fully deciding on a motor solution, capitalizing on fleeting opportunities and constantly adapting their motor output to align with the changing affordance landscape within the task environment.

Over the 30-second duration of the task, the individual is not merely repeating a motoric process but rather engaging in an organic assembly of motor-cognitive solutions. Each cycle of throwing and catching presents an opportunity to refine their strategy, ultimately leading to the emergence of a stable motor-cognitive solution that balances exercise intensity with successful task performance.

However, this stability is not static; rather, it represents a dynamically stable state in which the performer operates at an exercise intensity that is both physiologically sustainable and psychologically acceptable, reflecting their comfort with their current success rate. Importantly, the performer retains the capacity to adapt their motion and force parameterization if a single throw or catch is performed inadequately. Such adjustments may include modifications to posture, throwing mechanics (e.g., adopting a more advanced or simplified pattern), catching techniques (e.g., using one hand, two hands, or switching between dominant and non-dominant hands), or spatial translation of the body. This exemplifies the interwoven nature of cognition and action, where motor-cognitive solutions emerge as a holistic response to task and environmental demands shaped by the performer’s own capabilities.

The supine-to-stand-and-go task, like the throw-catch task, exemplifies a dynamic and complex interaction between perception and action, demanding explosive force production and rapid perceptual adjustments. The process of transitioning from a supine position to sprinting affords the individual to “act while deciding” by initiating the movement without committing to a predetermined strategy. The task, which requires maximum effort, further affords individuals to “decide while acting,” as they adjust their movements based on real-time perceptual and kinesthetic feedback. The task’s iterative nature—repeated for two trials—provides opportunities for individuals to refine their motor-cognitive strategies, inhibiting ineffective actions from previous attempts while modulating exercise intensity to maintain success within and across trials. Both tasks present a dynamic landscape of potential motor-cognitive solutions, inextricably linked to previous perception-action cycles. This paradigm facilitates ongoing adaptation and refinement of performance while accounting for an individual’s movement skill repertoire, including the multiple qualitative developmental levels associated with object projection, object reception, and locomotor

skills. Motor-cognitive DT paradigms that promote continuous decision-making afford a rich landscape for observing individual differences in motor-cognitive strategies, as participants explore and refine their motor-cognitive solutions [162]. Furthermore, motor-cognitive DT paradigms that afford continuous decision-making empower individuals to dynamically regulate complex sensorimotor interactions within the situated environment, exploring a vast repertoire of potential motor-cognitive strategies to optimize performance outcomes. This requires continuous calibration of embodied action in response to the evolving affordances of the task and environment. Accumulating a broad MC repertoire and optimizing coordination and control, often referred to as “skill”, requires considerable experience, gained through repeated, active exploration of movement possibilities and effort levels within contextually rich environments. Increased exposure to diverse skill practice within dynamic environmental contexts and varying task constraints enhance an individual’s ability to rapidly discern and effectively utilize task-relevant perceptual information and optimize performance. Ultimately, these experiences reduce the cognitive resources needed for skill execution and enhance an individual’s capacity to engage EFs to effectively adapt performance based on task-specific demands [163]. In [Figure 2](#), we offer a conceptual representation that demonstrates the spectrum of potential motor-cognitive solutions available across different skill levels. Comparatively, individuals with lower skill levels have a more restricted range of potential motor-cognitive solutions, primarily due to their less developed MC repertoire. This novel perspective on DT paradigm uniquely emphasizes the importance of an individual’s capacity to coordinate and control movements (i.e., skill level) and their accumulated context-specific experiences, while capturing learning-related and exercise-related mechanisms inherent in the concurrent development of MC and EFs.

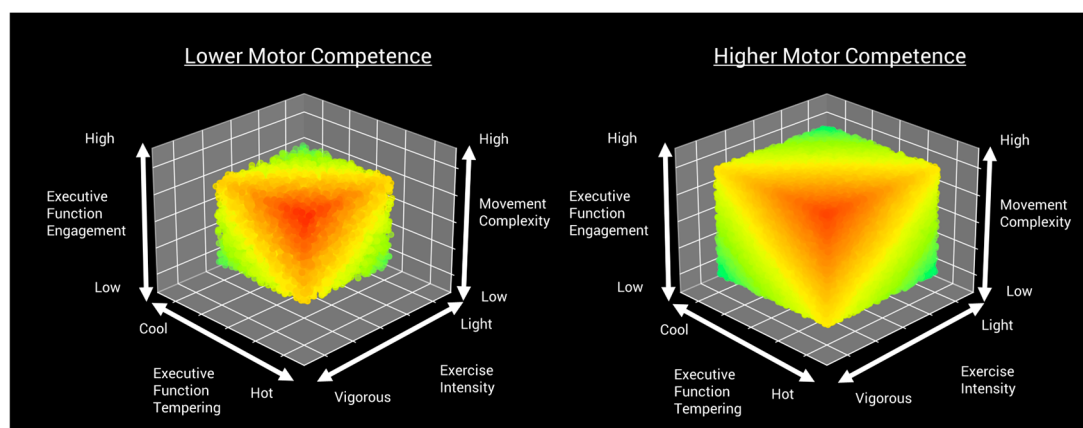


Figure 2. Motor Competence-Dependent Differences in Motor-Cognitive Solution Landscapes.

3.4. Impacts and Future Directions in Motor-Cognitive Research

This conceptual framework functions as a developmental model designed to enhance the sensitivity of motor-cognitive assessments, allowing for the longitudinal tracking of individual developmental trajectories. The model, represented in Figure 1, offers a novel framework to capture changes in movement complexity, exercise intensity, EF engagement, and EF tempering over time. This framework also provides a robust mechanism to observe how individuals adapt their perceptual-motor and cognitive systems to meet varying task demands and environmental constraints. This longitudinal perspective is critical for understanding how motor and cognitive systems concurrently adapt across developmental stages and illustrate how motor-cognitive solutions vary by individual but converge towards similar developmental outcomes. Importantly, this framework may serve as a foundation for developing more accurate tools to assess motor-cognitive development in diverse populations, with broad applications in educational, clinical, and sports contexts.

Although this approach promises substantial insights, applying such a multidimensional model presents inherent challenges, particularly in disentangling motor and cognitive contributions to task performance. Maurer and Roebers [13] demonstrated that difficult motor tasks are more strongly related to EFs than easier tasks, highlighting the critical role of task complexity in understanding the MC-EF link. However, the overlapping nature of motor-cognitive demands make it difficult to isolate their respective effects, which may introduce confounds when interpreting data. This challenge underscores the model's potential to identify areas requiring targeted intervention, allowing for more precise alignment of intervention strategies with motor-cognitive performance. As Hill and colleagues [164] emphasize, experimental studies must prioritize thorough process evaluations, enabling researchers to identify intervention characteristics that may exert causal or moderating effects. These insights are especially relevant in contexts that require tailored interventions, such as physical education, rehabilitation, and sports performance. However, capturing consistent data across ecologically valid and dynamic task environments may be complicated by variability in task, environmental, or individual factors. To mitigate these concerns, we encourage the use of both traditional and novel assessment paradigms, facilitating methodological comparisons. Furthermore, advanced techniques, including real-time neural and behavioral monitoring, may offer higher-resolution data, facilitating a clearer delineation of motor and cognitive influences.

Additionally, the framework facilitates comparative analyses between individuals, offering a means to assess variations in MC (see Figure 2). Mapping motor-cognitive solutions within this multidimensional space may provide a more nuanced understanding of how different individuals navigate similar task and environmental constraints, revealing distinct developmental trajectories shaped by both internal and external factors. These insights could enhance intervention strategies by enabling better tracking of motor-cognitive development over time.

This framework also facilitates a critical examination of both traditional and contemporary MC assessments, particularly in their capacity to capture the reciprocal influences of motor and cognitive demands on performance. The integration of “cool” and “hot” EF tasks into MC assessments—elements that have historically been disjointed or artificially incorporated—may serve as an initial validation. This approach can help determine whether both traditional and emerging motor-cognitive DT assessment methodologies effectively reflect the complex interactions between motor and cognitive processes. Furthermore, incorporating the contextualized assessment of “cool” and “hot” EFs into both traditional and contemporary MC assessments is crucial for developing motor-cognitive DT assessments that align with our novel view of the motor-cognitive DT paradigm. This refinement deepens our understanding of how motor and cognitive capacities are interwoven and shaped by developmental processes. Moreover, this enhanced understanding is particularly relevant in real-world environments, such as educational, clinical, and sports contexts, where ecologically valid assessments are crucial for capturing the dynamic and multifaceted nature of motor-cognitive interactions.

In conclusion, this framework provides a versatile tool for developmental tracking, comparative analyses between individuals, and the critical evaluation of assessment methodologies, while providing deeper insights into how motor-cognitive solutions emerge, stabilize, and adapt in response to ongoing task and environmental demands. Consequently, this framework not only enhances our understanding of individual developmental trajectories of MC and EFs but also offers a foundation for refining motor-cognitive and MC assessments to better capture the complexity and variability inherent in human development across the lifespan. Refined assessment methodologies and greater precision in identifying distinct developmental trajectories will ultimately improve our ability to target interventions, improving the relevance and effectiveness of interventions across real-world settings.

4. Conclusions

This theory-based conceptual paper aims to address critical limitations in existing assessments by proposing an integrated assessment paradigm that reflects the ecological validity and complexity

of real-world task environments. Specifically, we provide a conceptual bridge, grounded in multidisciplinary evidence, that effectively links the concurrent development of MC and EFs via learning- and exercise-related neurotrophic mechanisms, while also addressing existing gaps in the literature by considering the dynamic and reciprocal interactions between motor and cognitive systems across the lifespan. Our approach underscores the need for interdisciplinary research that integrates perspectives from motor control, cognitive science, exercise physiology, and neuroscience to develop a more comprehensive understanding of these interconnected processes.

By advancing the DT paradigm, we seek to provide a more nuanced perspective on motor-cognitive development, taking into account both "cool" and "hot" EFs. This necessitates consideration of the moderating effects of movement task complexity and an individual's established MC level to better capture the interconnected nature of motor and cognitive development. Most importantly, we advocate for motor tasks that promote continuous decision-making within ecologically valid (i.e., real-world) DT contexts, ensuring assessments reflect the complexity of everyday motor-cognitive demands. This paradigm holds significant potential to inform interventions across educational, clinical, and applied research settings by offering practical, evidence-based applications that support the enhancement of both motor and cognitive outcomes. Furthermore, it provides a comprehensive framework for developmental tracking, comparative analyses between individuals and cohorts, and the refinement of assessment methodologies, ultimately facilitating tailored intervention strategies that address the complexity and variability inherent in motor-cognitive development.

Rather than providing conclusions based on a comprehensive literature review, our aim is to emphasize the pressing need for interdisciplinary research that can serve as a foundation for future empirical studies and research syntheses. In doing so, this paper expands on the findings of Hill et al., [164], whose systematic review underscores the substantial need for research on the intertwined development of MC and non-motor domains. As a theory-based conceptual paper, this work does not adhere to formal inclusion criteria; however, we have drawn upon research spanning various levels of the evidence pyramid, including high-quality systematic reviews, empirical studies, and foundational theoretical frameworks. This approach ensures a well-rounded and comprehensive foundation for the proposed conceptual framework, capturing insights from across the research spectrum.

Ultimately, the advancements proposed in this paper offer promising new directions for embodied cognitive research, encouraging interdisciplinary collaboration and fostering a more integrative approach to studying motor-cognitive interactions across the lifespan.

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