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ELUCIDATING THE INTERDEPENDENCE OF MOTOR-COGNITIVE DEVELOPMENT AND PERFORMANCE

by

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ABSTRACT

As the development of complex coordination and control (i.e., motor development) involves the integration of neuromotor, psychological, social, and cognitive processes (i.e., executive functions), a better understanding of how these processes are embedded and manifest across stages of development throughout the lifespan is needed. The long-term processes associated with the acquisition and development of motor competence (MC), specifically, effortful practice and performance of various locomotor and object control skills, provide direct mechanisms for contributing to executive function (EF) development via different learning-related (e.g., synaptogenesis, hippocampal neurogenesis) as well as exercise-related (e.g., exercise-mediated neurogenesis, angiogenesis) mechanisms. However, traditional MC assessments use restrictive task protocols which limit cognitive involvement which effectively decontextualizes task performance. Recent MC literature has noted the role of motoric complexity, which has demonstrated stronger associations with cognitive performance. Specifically, motor-cognitive dual-task assessments afford moment-to-moment adaptations to coordination patterns (i.e., continuous decision-making) and empower individuals to regulate complex motoric and cognitive interactions within the individual-environment system via flexible and creative coordination patterns and strategies. Thus, the purpose of this dissertation was to examine performance levels in object projection (throwing speed vs throw-catch), locomotor (linear hop vs six-meter crossover hop), and functional coordination (supine-to-stand vs supine timed up-and-go) skills that represent different levels of task complexity within a convenience sample of

Army Reserve Officer Training Corps (AROTC) Cadets and compare the predictive utility of performance in these skills with individual and composite EF performance, controlling for cardiorespiratory fitness (CRF) levels. Skills with greater motoric complexity that require greater cognitive demands, demonstrated stronger associations with EF composite scores (r = -.434 – .280) compared to performance associated with more traditional skill assessments (r = -.286 – .167). In addition, HC-MC performance was a significant predictor of EF composite scores ($R^2 = 0.28$, $F_{6,52} = 3.37$, $p = 0.007$) when controlling for gender and CRF levels in this sample. These data provide preliminary evidence that when assessing the relationship between motor competence and executive functions, the level of gross motor complexity in assessments is an important factor to consider.

Keywords: motor skills, cognition, dual-task, measurement, complexity, perception-action

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ACC	Accuracy
AROTC	Army Reserve Officer Training Cadets
BDNF	Brain Derived Neurotrophic Factor
BMI	Body Mass Index
CRF	Cardiorespiratory Fitness
CVRT	Coefficient of Variation in Reaction Time
d’	*d*-Prime
EFs	Executive Functions
HC-MC	Higher Complexity Motor Competence
IGF-1	Insulin-like Growth Factor-1
MC	Motor Competence
MET	Metabolic Equivalent for Task
MSF	Musculoskeletal Fitness
RT	Reaction Time
T-MC	Traditional Motor Competence
VEGF	Vascular Endothelial Growth Factor

CHAPTER 1

INTRODUCTION

The foundation of a child's development is built upon the exploration of, and interaction with, the world via context-specific physical movement and can be defined as embodied cognition (Pesce & Ben-Soussan, 2016). Emerging research on the link between motor and cognitive development has provided a window to contextualize the integration between physical movement and cognitive development, as well as better articulate the potentially differential, yet synergistic, mechanisms (i.e., angiogenesis vs. neurogenesis) encapsulating brain growth and cognitive development (Adkins et al., 2006).

A specific outcome of high intensity movement (e.g., exercise) is the development of cardiorespiratory fitness (CRF), which supports cognitive development through the increased release of neurochemicals (e.g., brain derived neurotrophic factor [BDNF], insulin-like growth factor-1 [IGF-1], and vascular endothelial growth factor [VEGF]) during aerobic exercise. Increases CRF are linked to increases in brain volume (neurogenesis) and the formation of new blood vessels (angiogenesis) (Pereira et al., 2007). In humans, higher levels of CRF are also linked to elevated levels of BDNF and better performance on cognitive tasks (Dupuy et al., 2015; Stein et al., 2018). While increased cerebral blood volume (as a result of angiogenesis) in humans demonstrates improvements in cognitive performance (Pereira et al., 2007), providing an indirect measure of neurogenesis in humans, increased angiogenesis does not fully explain increases in neurogenesis (van Praag et al., 2007). The development of neuromuscular coordination and control required to perform a variety of motor skills (i.e., motor competence; MC) (Robinson et al., 2015) involves direct brain development mechanisms (e.g., synaptogenesis, hippocampal neurogenesis, connectivity within and between networks) that contribute to brain growth via skill acquisition (short-term) and retention (long-term). The development of MC, specifically, effortful practice and performance of various complex locomotor and object control skills, uniquely supports cognitive development via structural (i.e., the formation of new synapses; synaptogenesis) and functional changes (i.e., shifts in network connectivity) in the cerebellum (Diamond, 2000), basal ganglia (Leisman et al., 2014), and prefrontal cortex (Diamond, 2000) that occur as a result of the multiple domains of learning involved in skill acquisition (Tomporowski & Pesce, 2019) and complex skill training (Ben-Soussan et al., 2015).

Complex motor training that typically occurs in social settings (e.g., sports practice, physical education classes, recreational facilities, etc.) involves learning at multiple levels, including specific skill acquisition elements, navigating performance of skill in context-specific environments (i.e., integration), developing tactics for individual and game/sports contexts, and also offers opportunities for social learning via interactions with others. Each of these factors inherent to movement and learning positively impact executive functions (EF) development (Alvarez-Bueno et al., 2017; Pesce, Vazou, et al., 2021; Stodden et al., 2021). Complex motor training also facilitates the development of strength and power via inter-and intra-muscular coordination and control (e.g., motor unit recruitment, rate coding, synergistic muscle recruitment strategies; Stodden et al., 2014) and high levels of neuromuscular demand, which supports the development of CRF via continued participation in activities inherently involving performance of various motor skills

(Cattuzzo et al., 2016). Thus, the acquisition of MC throughout childhood and adolescence indirectly facilitates the development of EFs via multiple mechanisms (i.e., physiological – angiogenesis, structural – exercise-mediated neurogenesis).

Individuals lacking an adequate foundation of MC (e.g., throwing, kicking, jumping, hopping) needed to successfully participate in social physical activities (e.g., basketball, baseball, volleyball, etc.) where complex skill training typically occurs, may be less likely to participate in physical activities which may prevent them from developing higher levels of MC (Haubenstricker & Seefeldt, 1986; Stodden et al., 2013). Collectively, the lack of adequate movement development and adequate intensity of movement limits potential brain growth and EF development through differential physiological, structural, and functional mechanisms. Thus, strategies that promote the development of MC, and its application in various activities, may enhance cognitive development to a further degree than has been described by only CRF-related mechanisms.

1.1 Motor and Cognitive Development: An Integrative Perspective

As the development of complex coordination and control (i.e., motor development) involves the integration of neuromotor, psychological, social, and cognitive processes (i.e., executive functions), a better understanding of how these processes are embedded and manifest across stages of development throughout the lifespan is needed. As childhood is a critical period in the lifespan where gross locomotor skill development (i.e., quadrupedal and bipedal locomotor – crawling, running, jumping, hopping) and object control/projection (e.g., grasping, throwing, catching, striking) are foundational skills that improve an individual's capability to explore their environment, physically develop, learn, and socially interact with others (e.g., structured and non-structured play), it is logical that cognitive capabilities (i.e., executive functions) are developed concurrently. Specifically, as the development of many foundational motor skills generally occur in an intransitive, sequential, and cumulative manner (Clark & Metcalfe, 2002), with respect to the increasing complexity of perceptuomotor integration (i.e., with various aspects of the environment), acknowledging its central role as a catalyst for the development in other developmental domains is needed (Adolph & Hoch, 2019; Diamond & Ling, 2016; Pesce et al., 2018; Pesce, Stodden, et al., 2021; Rosenbaum, 2005).

Learning new motor skills and adapting previously acquired skills in various physical activity contexts (e.g., physical education, structured/unstructured play, sports) promotes enhanced exploration and exploitation of environmental contexts (i.e., affordances; Gibson & Gibson, 1955) subsequently enhancing behavioral flexibility, motor, and cognitive development. In addition, performance of motor skills in different contexts may further challenge core executive functions (i.e., inhibitory control, working memory, and cognitive flexibility) via the introduction of social interactions, cooperative learning, team tactics, and risk-reward analyses. Unfortunately, a comprehensive understanding of how motor and cognitive development occur concurrently is lacking, specifically with regard to the development of structural and functional integration and connectivity of different brain regions (Rosenbaum, 2005). Thus, the first study will provide a contemporary conceptual understanding of the concurrent development between motor and cognitive development across childhood and adolescence from a developmental perspective. Specifically, it will address how the development, maintenance, and enhancement of cognition is predicated on the inherently complex interactions that an individual has with their environment (e.g., navigating structures, manipulating objects, exploring sociocultural environments, etc.) where developing skillfulness is critical for success in these processes.

1.2 Current Issues with Motor Competence Assessment

Assessments currently used to measure MC in motor development literature are limited in their capability to capture cognitive/executive function processes involved in their performance (Rudd et al., 2020). Specifically, the focus of current MC assessments that measure gross motor skills emphasize movement pattern levels (i.e., the process of movement) or their resultant outcomes (e.g., speed, accuracy, distance, correct trials) via testing protocols and environments requiring limited cognitive effort (e.g., limiting opportunities to demonstrate multiple task solutions, generally self-paced tasks, restrictive task protocols) and have low ecological validity. For example, a task goal of simply throwing/running/jumping as fast/far as you can in a closed environment limits important salient environmental information, such as, visibility, wind, and/or other players, that would normally impact skill performance in more ‘real world’ performance settings. The lack of cognitive demand and ecological validity in current assessments restricts flexibility and adaptability in movement options that inherently require greater cognitive demands (e.g., evading defenders, passing to open teammates, creating strategies). In addition, typical cognitive assessments focusing on executive functions have historically either minimized the complexity of gross motor actions (e.g., Simon task, flanker, switch tasks) or incorporated gross motor actions in decontextualized tasks (e.g., Walking and counting; Walshe et al., 2015) and do not measure, nor accounting for, differences in motor skill performance levels. Thus, there is a need to address this assessment issue in these disparate, yet intricately related fields. Promoting assessments that more effectively demonstrate the interaction between motor and cognitive complexity, specifically across the developmental continuum, will concomitantly advance research in both motor development and neuroscience domains.

Motor (Lorson et al., 2013) and cognitive development (Germine et al., 2011; Hartshorne & Germine, 2015) have generally been suggested to plateau by early adulthood. Thus, early adulthood may be the most salient age group to more effectively elucidate the relationship between motor development and cognitive development, specifically by implementing novel complex movement assessments that have greater ecological validity and require greater cognitive demands. Thus, the second study will examine the relationship between MC assessments with varying levels of task complexity and EFs in young adults.

1.3 Purpose

Study 1 The Role of Task Complexity in Motor and Cognitive Development

The purpose of Study 1 was to a) provide a conceptual understanding of the concurrent development between motor and cognitive development across childhood and adolescence from a developmental perspective and b) provide new insight for assessment that addresses the inherent complexities of 'real world' performance that will elucidate this relationship more effectively.

Study 2 Examining Relationships Between Motor Competence Assessments with Lower and Higher Complexity and Executive Functions

The purpose of Study 2 was to examine performance of skills that represent different levels of task complexity (object projection – throwing speed vs throw-catch; locomotor – linear hop vs six-meter crossover hop; functional coordination – supine-to-stand vs supine timed up-and-go) and their predictive utility with composite EF (inhibitory control, working memory, and cognitive flexibility) scores in a convenience sample of young adults. A descriptive-analytic cross-sectional design will be used to examine the relationships between different levels of motor skill task complexity and EF performance scores, controlling for cardiorespiratory fitness levels.

1.4 Significance and Innovation

Significance

Appropriate measurement of MC and EFs is critical to understanding the relationship between these two constructs, and ultimately, to improve motor skill development and cognition via MC interventions. Previous research has documented a range of correlations between MC and EFs ranging from no relationship (R = -.03; Ludyga et al., 2019) to moderately related (R =.35; Maurer & Roebers, 2019). This wide range in the strengths of correlations may be partially attributed to differences in how MC and EFs were assessed, although the limitations of assessment have not been adequately addressed in previous research. This dissertation will address this knowledge gap and add to the literature base in this area. However, even without a definitive understanding of the relationship between MC and EF, research supports the notion that underlying neurophysiological mechanisms (i.e., structural and functional connectivity within and between neural networks) between MC and EF performance are intricately linked (Diamond, 2000; Leisman et al., 2016). Additionally, interventions that show improvements in MC also demonstrate increases in various domains of EF (Diamond & Ling, 2016; Ludyga et al., 2019; Van Der Fels et al., 2015). A caveat to specifying the nature of this relationship is that individuals must be adequately challenged by task complexity (Crova et al., 2014; Diamond & Lee, 2011; Diamond & Ling, 2016; Pesce, 2012). Recently, initial evidence has shown that greater motor task complexity may demonstrate a stronger relationship with EFs (simple task R =.18, complex task R =.35) than was previously thought to exist (Maurer & Roebers, 2019). However, Maurer and Roebers (2019) may have inadvertently constrained potential task solutions, thus limiting flexibility in skill performance characteristics (i.e., developmental skill levels) and decreasing the ecological validity of their assessments.

The field of motor behavior recognizes the importance of task complexity in MC and EF relations (Fischer, 1980; Fowler & Leithwood, 1971; Rosenbaum, 2005); however, due to a lack of research examining the inherent complexities in addressing the MC–cognition relationship, there is a need to develop new assessments that not only capture differences in MC levels and capabilities in a wide range of skills (e.g., motor repertoire) but also enhance assessment of cognitive capabilities (i.e., hot and cool EFs). As cognitive demands and ecological validity are currently limited in current MC assessments, it limits our understanding of the potential strength of association between MC and EFs. Thus, there is a critical need to examine the relationship between MC and EFs with a more focused consideration of the complexity of tasks being assessed and better appreciate the developmental mechanisms associated with its relationship to EFs. This study is significant as it will advance our understanding of the role that task complexity plays in the relationship between the development of MC and EFs. The results of this dissertation will have implications for future assessments of MC and EFs by testing assessment methods that will more effectively, via differentiating complexity in motor skill tasks, address the relationship between MC and EFs and how this relationship develops.

Innovation

The focus of this dissertation is innovative as it will expand previous research in motor development and neuroscience by better linking MC and EFs via novel dual-task assessments that inherently require increased levels of cognition and acknowledge the importance of the development of an individual's skill repertoire (i.e., skillfulness). It also will be the first to examine how differences in motor complexity via assessing multidimensional (i.e., object control, locomotor, and postural control capabilities in one task) and unidimensional (i.e., only requiring one skill) MC tasks impact the relationship between MC and core EFs (i.e., inhibitory control, working memory, and cognitive flexibility) with differing levels of MC task complexity. We are proposing the concurrent development of MC and EFs are established through increasingly complex interactions with an individual's environment. As a consequence of our novel approach to dual-task assessments, we hope this dissertation will spur additional interdisciplinary research in motor development and neuroscience by more effectively identifying the link between MC and EFs.

CHAPTER 2

STUDY 1: THE ROLE OF TASK COMPLEXITY IN MOTOR AND COGNITIVE DEVELOPMENT

2.1 Introduction

The development of motor competence (MC) is essential for an individual to continue to perceive, navigate, and explore the physical world and may be a critical antecedent for enhanced functioning in other developmental domains (e.g., cognitive, psychological, social, and emotional). Embodied learning theories encourage experiences that promote the exploration of novel and challenging bodily states, which inherently requires the development of a foundation of competency in a variety of movement forms (e.g., locomotor, object control/projection, postural control; Stodden et al., 2021). In addition, core executive functions (EFs) play a critical role in the complex and continuous nature of decision-making and regulating behavior in embodied performance settings. Providing opportunities that enable children and adolescents to expand their capacity to perceive, navigate, and explore their physical and sociocultural environments as well as develop emotional skills by participating in physical activities that require emotional regulation (e.g., structured and unstructured play, sports practice and games) is critical for promoting the development of MC and EFs (Stodden et al., 2021). The purpose of this paper is to provide a conceptual bridge to effectively link the concurrent development of MC and EFs via direct (e.g., synaptogenesis, hippocampal neurogenesis, connectivity within and between networks) and indirect (e.g., angiogenesis, exercise-mediated neurogenesis) mechanisms and to formalize this conceptual bridge with exemplars for assessment.

2.2 Executive Functions

EFs are conceptualized as a group of top-down processes which allow an individual to regulate volitional behavior and successfully manage their actions in accordance with their task goals (Diamond, 2013). EFs are employed in everyday situations to promote or suppress behaviors, switch between tasks, and adapt behavioral strategies (Barkley, 2012; Goldstein & Naglieri, 2014). Three core EFs needed to build more complex EFs are: (1) Inhibitory Control, the ability to suppress or resist an automatic response in order to make a less automatic, but task-relevant response, (2) Working Memory, the active replacement of no longer relevant information with newer task-relevant information in working memory, and (3) Cognitive Flexibility, the ability to switch between task sets or response rules, even in the presence of proactive interference or negative priming (Miyake et al., 2000). These three core cognitive processes play a critical role in the development and performance of motor skills across the lifespan (Diamond, 2013; Diamond & Ling, 2016; Miyake et al., 2000). As EFs are used to regulate volitional behavior, they can be applied in various contexts across an emotional-motivational continuum (i.e., contexts with minimal motivation or contexts predominantly driven by emotion/motivation). Traditionally EFs have been dichotomized into those applied in contexts with minimal incentive and/or emotional intensity (i.e., cool EFs); and those applied in contexts where emotional-motivational aspects of behavior are intensified (i.e., hot EFs) (Zelazo & Carlson, 2012; Zelazo & Müller, 2002).

Cool EFs

Traditional views on cognition have focused on the development and maintenance of mental processes that support goal-directed and future-oriented behaviors in relatively decontextualized, analytical, and emotionally detached testing conditions (i.e., “cool” EFs) (Miyake et al., 2000; Peterson & Welsh, 2014). Clinical observations in early research regarding focal brain damage documented distinct differences between damage to the frontal cortex and damage to posterior areas of the brain which revealed patients lacked the ability to use basic cognitive functions to adapt their behaviors to meet future task-goals (Luria, 1966; Tueber, 1964). This focus led to investigations surrounding cognition that were heavily centered around the relationship between frontal lobe structures and future-oriented behaviors essential to adaptive behavior (Duncan et al., 1995; Fuster, 2001; Luria, 1966; Pribram, 1969; Stuss & Benson, 1984). As a result, researchers created frameworks that focused on frontal lobe structures and emphasized cognitive functions mediated by the prefrontal cortex (Peterson & Welsh, 2014). This research led to the discovery of the cingulo-opercular and fronto-parietal networks, both of which are used for cognitive control (Dosenbach et al., 2007).

The cingulo-opercular network is believed to promote the maintenance of task-relevant goals and incorporate error-based adjustments to behavior; whereas the fronto-parietal network is associated with executive control during task execution and facilitates selective attention of trial-relevant information. Researchers hypothesized that by studying patients with damage to the prefrontal cortex, a critical brain region in both the cingulo-opercular and fronto-parietal networks, they could explain decrements in EFs. However, patients with PFC damage performed well on EF assessments, but uniquely demonstrated behaviors that could be described as poor social regulation and increased impulsivity in social decision-making (Bechara, 2004; Bechara et al., 1994). Thus, researchers began to investigate context-specific applications of EFs recruited in emotional-motivational aspects of risk-reward analyses and decision making (Bechara et al., 1994), now commonly labeled "hot" EFs.

Hot EFs

The perception of emotionally salient stimuli can significantly impact cognitive performance (Okon-Singer et al., 2015). Thus, the ability to selectively respond to relevant aspects of the environment while inhibiting potential distractions (i.e., emotionally-charged cues) and competing choices of action is critical for managing behaviors to achieve task-goals (Desimone & Duncan, 1995; Miller & Cohen, 2001). "Hot" EFs serve an important role in filtering out emotionally-irrelevant information (i.e., emotional gating) to optimize the capacity of working memory as representations of task-sets, goals, and other task-relevant information are ever-changing (Miller & Cohen, 2001; Stout et al., 2015). Individuals commonly use "hot" EFs to flexibly choose emotion regulation strategies to adapt to situational demands (Sheppes & Levin, 2013). More specifically, individuals recruit "hot" EFs in social environments to self-regulate stimulus-driven responses such as reward processing, social behavior, and affective decision-making (Leshem, 2016) to promote successful interactions with others.

The regulation of "hot" EFs are associated with activity in the ventromedial prefrontal cortex and caudal orbitofrontal cortex (Fuster, 2001) and are linked to the default mode network which is responsible for aspects of social cognition (Schilbach et al., 2008). "Hot" EFs critically depend on appropriate levels of default mode network activity to regulate limbic functions in contexts where emotional-motivational aspects of behavior are intensified (Barbas, 2000; Otero & Barker, 2014; Padoa-Schioppa & Conen, 2017; Zelazo & Müller, 2002). Labeling EFs as either "hot" or "cool" may provide unique insights into the functions of individual aspects of behavior function, however, this restrictive approach neglects the interconnectedness and blending of EFs that occur in 'real world' situations.

Hot–Cool Gradient

As information processing in the brain relies on complex reciprocal interactions within- and between-networks, the question of whether brain processes associated with "emotion" can be definitively separated from those associated with "cognition" has been debated as cognition includes both emotional and logical information (Okon-Singer et al., 2015; Pessoa, 2008; Petrovic & Castellanos, 2016). Zelazo & Müller (2002) suggested that "cool" and "hot" EFs exist on discernable ends of a continuum, allowing an individual to simultaneously activate "hot" and "cool" EFs at varying intensities in order to explore and meaningfully interact with their environment. For example, individuals engage core EFs (e.g., inhibitory control, working memory, cognitive flexibility) to act on both emotional/motivational and logical information (Zelazo & Müller, 2002). Evidence from meta-analyses of neuroimaging studies surrounding "cool" EFs supports the hypothesis of a "hot-cool" EF gradient, as traditionally "cool" tasks (e.g., stop-signal, go/no-go, flanker, Simon) elicited activity in brain regions associated with emotions (e.g., ventrolateral prefrontal cortex and anterior insula), suggesting functional relationships between "cool" and "hot" brain regions (Cieslik et al., 2015; Nee et al., 2007). In addition, a practical, and likely successful, approach to solving emotionally laden problems is to create "psychological distance" from the situation (Sigel, 1968), reconceptualize the issue in a decontextualized perspective, and then apply “cool” EFs to solve the issue (Carlson et al., 2005; Mischel et al., 1989).

The development of EFs relies on structural and functional connections between brain regions for increasingly complex levels of cognitive functions over the lifespan (Uddin et al., 2011). The brain utilizes these structural and functional connections to dynamically balance the segregation (within-network) and integration (between-network) of neural processes in relation to task-relevant demands imposed by the task-goal of the performer (Cohen & D’Esposito, 2016; Mohr et al., 2016; Reijneveld et al., 2007).

2.3 How Can Executive Functions Be Improved?

With an understanding of how EFs have been described and the interconnections across brain regions and their respective neural networks involved in everyday tasks, a logical direction forward is to understand is how the development of EFs occurs. Voluntary movement that is planned, structured, and purposefully focused on improvement or maintenance of one or more components of physical health (i.e., exercise; Dasso, 2019) is a well-known tool for maintaining and improving neurocognitive health in across the lifespan (Diamond & Ling, 2019; Moore et al., 2022; Pesce, Vazou, et al., 2021). However, learning-related (e.g., synaptogenesis, hippocampal neurogenesis) vs. exercise-related (e.g., exercise-mediated neurogenesis, angiogenesis) mechanisms underlying structural and functional changes within the brain is a critical consideration when determining how improvement/development of EFs occur (Pesce, Vazou, et al., 2021). From a developmental lens, the continual learning that occurs from infancy (specifically from a movement perspective) that can be extrapolated based on the intransitive, cumulative, and sequential nature of motor development, speaks to the importance of differentiating the influence of these learning-related and exercise-related EF promotion mechanisms.

Learning-related Mechanisms

The human brain is a dynamic organ that adapts both structurally and functionally to meet environmental demands. Current evidence supporting learning-dependent changes in brain morphology and function are supported from studies investigating the effects of perceptual learning on the reorganization of representations within sensory-cortical areas (Recanzone et al., 1992; Recanzone et al., 1993). Acquiring the capability to navigate the world successfully and progressively (i.e., Motor learning/development) drives cerebral plasticity (i.e., structural and functional adaptations) via co-localized learning-dependent synaptogenesis and functional reorganization in specific regions of the cortex that mediate the acquisition and retention of skilled motor behavior (Kleim et al., 2002; Kleim et al., 2004). Initial acquisition of movement coordination and control develop via functional changes in neural network dynamics (i.e., functional connectivity) and may result in marked improvements in physical performance over the course a single training session (Doyon & Benali, 2005; Doyon et al., 2002). Over time, practice promotes more permanent structural changes (i.e., synaptogenesis, hippocampal neurogenesis) in the brain (Dayan & Cohen, 2011; Doyon & Benali, 2005) and is exemplified via improved control and consistent performance. Functional and structural changes associated with skill acquisition also critically support EFs via decreased cognitive demands during skill performance and increased levels of gray matter within the brain.

Skill Acquisition and Brain Development

The fronto-parietal and default mode networks are key areas where functional changes in activation are associated with skill acquisition (Hikosaka et al., 2002). Specifically, fronto-parietal (associated with executive control) and default mode (associated with automaticity) network functions are inversely related to one another and increased levels of activation in the default mode network may reflect a shift from more cognitively controlled to automatic task performance (Patel et al., 2013). In addition, "good" learners decrease activation of the fronto-parietal network and increase activation in the default mode network more quickly than "poor" learners while performing a visuo-motor task (Sakai et al., 1998), suggesting that functional decreases across nodes within the fronto-parietal network may serve as key neural markers of learning. Thus, the default mode network is typically activated under conditions of low attention demand and is inversely related to task complexity (i.e., activation decreases with more complex tasks) (Gusnard & Raichle, 2001; Mayer et al., 2010; McKiernan et al., 2003). The default mode network may play an important role in the acquisition of motor skills as greater activation in the default mode network represents a decreased demand for executive-controlled attention and an increase in cognitive resources that can be used to explore internal thoughts, memories, and future goals (Patel et al., 2013), which are critical in decision-making. The activation of the fronto-parietal network is likely used to allocate attentional resources to relevant features in the environment (Cisek, 2007; Pezzulo & Cisek, 2016), thus biasing the use of perceptual information for decision-making and creating less demand for executive control. In addition, decreased activation of the fronto-parietal network may release cognitive resources (via increased activation of default mode network) needed for the varying intensities of EFs along the “hot-cool” neurobiological gradient that are involved in skill performance in ‘real world’ contexts. Thus, the transition from fronto-parietal network to default mode network activation may reflect a key change in functional network dynamics that is associated with skill acquisition and supports EF development. Reallocation of attentional resources via functional changes in network dynamics may explain some of the benefits of skill acquisition, however, increases in synaptogenesis and neurogenesis also serve unique roles in improving EFs.

Retention

While initial stages of motor learning (acquisition) are associated with functional changes in network dynamics (Doyon & Benali, 2005; Doyon et al., 2002), later stages of motor learning (i.e., retention) are primarily associated with structural plasticity (growth) in gray matter (Draganski & May, 2008). Motor learning is associated with changes in the cerebellum (Diamond, 2000), basal ganglia (Leisman et al., 2014), hippocampus (Deng et al., 2009), and prefrontal cortex (Diamond, 2000), which may be due to the multiple domains (e.g., social-emotional, psychological, cognitive, physical) involved with skill learning. Two prominent training-evoked gray matter changes associated with post-acquisition stages of motor learning are synaptogenesis and neurogenesis. Significant increases in synaptogenesis are not detectable until the second, slower phase of learning (i.e., retention) (Kleim et al., 2004), which can occur either as the result of dendritic branching or increases in the number of synapses along existing dendrites (Kleim et al., 2002; Kolb et al., 2008). Complex skill training produces significantly more synapses than less complex training (Kleim et al., 1998) which may lead to greater improvements in EFs via increased levels of synaptogenesis associated with skill learning. Increases in synapses impact cell signaling and network communication, making synaptogenesis an important factor in the activity-dependent reorganization of neural networks in the adult brain. Individuals with better performance on EF assessments have demonstrated more efficient network communication (Baum et al., 2017). Thus, synaptogenesis may improve neural transmission cost-efficiency (i.e., lowering the network cost of transferring information) and lead to improvements in EFs. However, the total cost of neuronal computations is not only dependent on how neurons are connected to one another, but also on the individual function (i.e., health) of each neuron.

Learning that is effortful and sustained over time has proven to be the most effective strategy for keeping new neurons alive (Waddell & Shors, 2008). Thus, tasks that have a slower acquisition rate (i.e., complex tasks) are more likely to rescue cells from death than training with tasks in which learning occurred quickly (Shors, 2014; Waddell & Shors, 2008). Conversely, tasks with faster acquisition rates (i.e., simple tasks) that are easily mastered will require less effort throughout the learning process and produce fewer cognitive benefits. Thus, maintaining an optimal challenge point between the developmental level of the learner and the complexity of the task is needed for successful performance, which sustains intrinsic motivation to continue to learn (Guadagnoli & Lee, 2004).

Exercise-related Mechanisms

Two of the most commonly studied pathways in the exercise-cognition relationship are the release of BDNF and IGF-1 (Cotman et al., 2007; Dishman et al., 2006; Stillman et al., 2016). BDNF and IGF-1 are causally linked to cognitive improvements after exercise as blocking signaling in these pathways eliminates or attenuates the positive effects of exercise on long-term potentiation, a pathway related to cognition, in mice (Cotman et al., 2007). Blocking BDNF specifically attenuates behavioral learning and memory in mice following exercise, thus demonstrating the link between BDNF mechanisms and cognition (Vaynman et al., 2004). Further, blocking IGF-1 receptors prevented exercise-induced increases in BDNF suggesting that BDNF and IGF-1 pathways are interdependent and eventually converge (Carro et al., 2000; Ding et al., 2006).

Exercise-induced improvements in EFs stem from exercise-mediated neurogenesis and may also have an interdependent relationship with the angiogenesis, as changes in neurovasculature precede neurogenesis in rodents (van Praag, 2008). In addition, animal studies have suggested that cognitive changes only occur when new neurons successfully integrate themselves within existing cellular networks (Bruel□Jungerman et al., 2005; Vivar et al., 2012); thus, demonstrating the critical role of increasing the growth of blood vessels within the brain to stimulate cell proliferation and survival. Angiogenesis is a complex, multistep process of cellular changes resulting from increased levels of growth factor production and up-regulated molecular interactions and transactions (Stillman et al., 2016) that uniquely vascularizes the brain (Bär, 1980; Risau, 1992). Vascular endothelial growth factor (VEGF) is released in hypoxic tissues (Marti et al., 2000) and has a primary role in the overall control of neural angiogenesis (Virgintino et al., 2003). Evidence supports the use of aerobic exercise (i.e., exercise-induced hypoxia) as an effective strategy for promoting angiogenesis in the brain and improving cognitive performance (Pereira et al., 2007). Additionally, researchers found a relationship between higher levels of cardiorespiratory fitness (CRF) and better performance on tasks of EF (Aberg et al., 2009; Hwang et al., 2017; Voss et al., 2011). While moderate to vigorous physical activity increases CRF and has been associated with increases in EF performance (Alghadir et al., 2016; Janssen et al., 2014), the level of cognitive involvement during physical activity influences the extent that an individual experiences cognitive benefits (Pesce, Vazou, et al., 2021).

Developmental Perspectives on MC and EFs

The development of MC concurrently promotes the development of cognitive structures via motor learning (i.e., acquisition and retention) and exercise-related mechanisms (e.g., BDNF, IGF-1, angiogenesis, neurogenesis) via movement intensity (i.e., effort and persistent activity). To understand how this relationship occurs from a developmental perspective, we examine how perception, action, and decision processes are deeply intertwined and involve increasingly complex interactions within the individual-environment relationship.

Developmental changes in cognition and motor skills are a product of an individual's interactions with their environment that occur across multiple time scales (i.e., seconds, days, years) through continuous perception-action cycles (Mulder et al., 2017). Individuals concurrently and directly develop MC and EFs through active exploration of the surrounding environment (motor learning mechanisms). To accomplish any movement-related task, an individual must identify relationships between task/environmental characteristics and the individual's own movement capabilities to establish actionable qualities of the performance environment (i.e., affordances; Gibson, 1979; Newell, 1986). As such, the performance of any action is coupled with perceptions of defining constraints of the task, environment, and the individual (Davids et al., 2008; Newell, 1986). To make control possible, an individual must regulate the complex interactions that occur within the individual-environment system.

One method for regulating complexity in early stages of movement development is to reduce or “freeze” degrees of freedom within the motor system (e.g., muscles, joints, limbs) to optimize control and develop coordination states that support goal-directed actions (Davids et al., 2003; Turvey, 1990). For example, at the onset of independent walking infants will “freeze” their arms in a high-guard position above the head to decrease complex physical demands needed for dynamic postural control (Bril & Brenière, 1993). As salient perception-action couplings become more frequent (through effortful practice), the infant will begin to “un-freeze” degrees of freedom (i.e., allowing the arms to move), subsequently leading to the discovery of affordances within the environment (e.g., via locomotion) and insight into object properties and spatial relations (Gibson, 1988; Gibson, 1979). The acquisition and retention of walking requires the infant to 1) *Inhibit* primitive neuro-motor synergies (e.g., symmetrical coupling of the upper limbs; Lazarus & Todor, 1991), 2) Use *working memory* to begin self-navigating using landmarks (Campos et al., 2000), 3), *Flexibly* shift attention between interacting with objects (e.g., blocks, chairs, toys, etc.) and enhanced environment navigation. Thus, the “education of attention” through active exploration within the task-environment (e.g., searching for task-relevant perceptual information) not only promotes MC development, but directly promotes the development of core EFs.

Although there is a general belief that MC in many skills is developed “naturally,” the complexity inherent in its intransitive, sequential, and cumulative, progression requires perceptually rich and dynamic environments to effectively establish perception-action couplings that improve an individual's capacity to functionally interact with key constraints (i.e., task and environmental) in order to exploit them and successfully achieve a task-goal (Davids et al., 2013). Notwithstanding relevant motor learning literature regarding constant versus variable practice schedules for optimal skill acquisition; another commonly held belief is that breaking down complex tasks and tightly controlling environments (which result in decomposed and decontextualized tasks) benefits skill acquisition and learning (Magill & Lee, 1998). As mentioned previously (see learning-related mechanisms), tasks with slower acquisition rates (i.e., complex tasks) promote higher levels of FPN activation (O'Connell & Basak, 2018; Shashidhara et al., 2019) and promote synaptogenesis (Kleim et al., 2002; Kleim et al., 2004) and hippocampal neuron survival (Shors, 2014 2008); indicating that complex tasks are more effective for developing MC and EFs.

Individuals also indirectly support the development of EFs through the effortful practice and performance of various motor skills (e.g., running, jumping, hopping, throwing, kicking, etc.) needed to develop MC (exercise-related mechanisms). Specifically, the contexts surrounding the development of MC (e.g., structured and unstructured play, sports, specific skill practice) provide individuals with opportunities for participation in moderate-to-vigorous physical activities and subsequently develop of CRF and musculoskeletal fitness (MSF) (Cattuzzo et al., 2016; Stodden et al., 2014). Participation in moderate-to-vigorous physical activities promote angiogenesis, which leads to increased levels of CRF, is associated with improved performance on EF tasks (Alghadir et al., 2016; Janssen et al., 2014). Physical activities that require complex multi-joint coordination (e.g., gymnastics, baseball/softball, soccer, etc.) also stimulate the development of MSF via inter- and intra-muscular recruitment strategies (Stodden et al., 2014). However, evidence focusing on associations between MSF and EFs is limited and warrants investigation. In addition, an individual's skill level (i.e., MC) effects their energy expenditure levels (Sacko et al., 2019; Sacko et al., 2021) and may consequently impact neurocognitive benefits. Thus, focusing on the development of MC also indirectly supports EFs via exercise-related mechanisms (i.e., angiogenesis and exercise-mediated neurogenesis).

2.4 Motor Competence Assessments

We believe there is a critical need for the advancement of MC assessments used in MC-EF paradigms based on the role of MC in the development of EFs via learning- and exercise-related mechanisms. In this section, we discuss a novel approach to MC-EF paradigms and offer novel exemplars of motor tasks that involve greater motoric complexity and that more effectively align with 'real world' performance environments (i.e., greater ecological validity). In addition, development of novel assessments that are developmentally valid across a wide age range (i.e., childhood through adulthood) also allows for the concurrent assessment of EFs across a wide age range, facilitating the ability to assess both the development of MC and EFs across time. This novel combination of assessment factors also aligns with a developmental perspective in that the assessments effectively capture the development of embodied cognition across time.

Limitations of MC Assessments for Alignment with Executive Functions

Current MC assessments measure movement pattern levels (i.e., movement process) or their resultant outcomes (e.g., speed, accuracy, distance, correct trials) using protocols that limit their applicability to 'real world' contexts, and therefore limit their capability to capture cognitive/executive function processes involved in ecologically valid performance contexts (Rudd et al., 2020). Inhibitory control, working memory, and cognitive flexibility (i.e., core EFs) critically support decision-making and problem-solving processes needed to effectively and efficiently adapt behaviors to achieve task-goals in ‘real world’ contexts (Diamond, 2013). For example, many MC assessments require individuals to perform discrete tasks in a way that limits the integration of salient environmental influences that impact skill performance (e.g., throwing for speed, standing long jump, supine-to-stand); effectively decontextualizing the assessment and disregarding the complex and continuous nature of decision-making in embodied performance settings. In this section, we discuss a novel approach to MC-EF paradigms and offer exemplars that are developmentally appropriate (i.e., considers the skill level of the learner) with consideration to embodied decision-making.

Discrete decisions are a common limitation in MC tasks within MC-EF paradigms (i.e., throw/jump/kick/run as hard/fast as you can). In these scenarios, the decision-maker’s performance choice will not impact the availability of potential movement solutions and the choice itself is generally self-paced and decontextualized as demanded protocols set the conditions for performance (e.g., throw as hard/fast as you can to a wall at a specific distance). Discrete MC tasks that require specific protocol demands limit participant decision-making either purposefully or inadvertently and trivialize the effects of action dynamics on subsequent perception dynamics (i.e., perception-action loops). The theoretical implications behind discrete decision-making tasks propose a serial view of decision-making (Fodor, 1983; Pylyshyn, 1984) in which the decision-maker perceives the task/environmental affordances, chooses between predefined task solutions (due to restrictive task protocols), and acts on the decision (i.e., decide-then-act). Most current discrete MC tasks situated within test batteries require specified execution protocols to enable greater experimental control. Unfortunately, these tasks may have distorted our view of MC-EF relations by promoting stable (i.e., closed skill) environments and predefined task solutions, thus trivializing perception-action dynamics. Alternatively, tasks that promote continuous decision-making that occur over extended performance timeframes provide a continuum of potential solution adaptations that are affected by recent responses and are continuously subject to change (Yoo et al., 2021). The dynamic nature of continuous decision-making opens avenues for researching not only questions of control (e.g., how to catch a ball), but also those of timing (i.e., exactly when to initiate the action) (Yoo et al., 2021). Continuous decision-making can be applied in both continuous tasks (i.e., no predefined beginning or ending) or repeated performances of discrete skills. In continuous decision-making, the decision-maker can "act while deciding" by initiating actions before completing the decision to exploit options that would otherwise disappear (e.g., running towards defenders while searching for open gaps) or to buy time (Barca & Pezzulo, 2012). Additionally, the decision-maker can "decide while acting" by adapting their performance as a result of perceiving novel affordances, gathering novel information, or reconsidering a previous decision (Resulaj et al., 2009). Thus, core EFs (e.g., inhibitory control, working memory, and cognitive flexibility critically support decision-making and problem-solving processes needed to effectively and efficiently adapt behaviors in these types of tasks in order to achieve task-goals in these types of 'real world' contexts (Diamond, 2013).

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

Motor-cognitive dual-task (referred to hereafter as dual-task) paradigms may provide a “jumping off point” as they capture cognitive involvement in movement actions across various types of tasks, provide multiple combinations of potential task solutions, and are representative of dynamic everyday life contexts (Huang & Mercer, 2001). Traditional dual-task paradigms focus on the application of EFs to flexibly allocate attentional resources between two distinct tasks (e.g., walking and counting; Walshe et al., 2015), but may sacrifice ecological validity by oversimplifying the motoric context and thus, the cognitive demands of the task. Providing an assessment paradigm that promotes continuous decision-making by allowing flexibility in skill performance characteristics (i.e., different skill levels) to enhance task performance is an alternative way to examine an individual’s cognitive function and is a more ecologically valid paradigm. For example, allowing for choice between different motor solutions or adaptations to a previously attempted motor solution in continuous decision-making tasks (e.g., continuous and/or repeated discrete skills) requires increased levels of core EFs to update feedback from previous performances, inhibit ineffective motor actions, and flexibly attend to both motor and cognitive aspects of task performance. This assessment scenario enhances online decision-making capabilities and speaks to the importance of being able to demonstrate advanced skill levels. Advanced skill levels allow an individual to choose different qualitative coordinative patterns within a skill (i.e., different developmental levels) and different levels of force regulation within a specific coordinative pattern (i.e., control) in order to successfully accomplish the task goal. Thus, advanced skill levels offer flexibility in motor solutions that are predicated on an individual’s ability to choose an acceptable solution to a task based on either success or failure of meeting the task goal and modify, if necessary, performance based on continuous feedback from previous performances (i.e., working memory). In developing this advanced motor skill repertoire (i.e., experiential learning), both within a skill and across a wide foundation of skills, the application of EFs (e.g., inhibitory control, working memory, and cognitive flexibility) are inherently integrated in developing skill (i.e., embodied cognition).

Hulteen and colleagues (2022) allude to this concept by promoting dynamic and continuous tasks (e.g., throw and catch, supine-to-stand [and go]) that offer a continuum of coordinative solutions which are inextricably linked to previous within-task responses and affords moment-to-moment adaptations in coordination patterns. Dual-task paradigms with continuous decision-making requirements allow for considerable amounts of individual variation in coordination patterns and strategies as individuals seek to assemble their own coordinative solutions. Further, dual-task paradigms that afford continuous decision-making empower individuals to regulate complex motoric and cognitive interactions within the individual-environment systems via flexible and creative coordination patterns and strategies (e.g., "freezing" or "releasing" degrees of freedom, decreasing or increasing force, increasing or decreasing choice reaction time). In essence, developing a broad repertoire of MC skills and various coordination patterns and force regulation capabilities within skills requires considerable experience, active exploration of skill execution options, and effortful practice in context-specific environments. Increased experiences and opportunities to practice skills in various environmental contexts enhances the ability to identify and optimally utilize task-relevant perceptual information quickly and effectively, ultimately decreasing the cognitive resources allocated to skill execution and increasing the capability to recruit EFs to successfully execute and adapt performance. This novel view of dual-task paradigms acknowledges the importance of the individual's motor repertoire (i.e., their skillfulness), context-specific experiences, and the learning-related mechanisms inherent in the concurrent development of MC and EFs.

2.5 Conclusion

We contend that advancing MC assessments by promoting integrative approaches to MC-EF paradigms with consideration to interactions between learning- and exercise-related mechanisms will more effectively capture the underlying processes of motor and cognitive development. This paper provides insight and rationale to promote motor tasks that involve greater motoric complexity and require continuous decision-making that more effectively align with 'real world' performance environments. Advancing MC assessments will provide a better understanding of how motor and cognitive processes are embedded and manifest across stages of development and continue to promote MC as a critical component for holistic human development.

CHAPTER 3

EXAMINING THE IMPACT OF MOTOR ASSESSMENT COMPLEXITY ON THE RELATIONSHIPS BETWEEN MOTOR COMPETENCE AND EXECUTIVE FUNCTIONS

3.1 Introduction

Approximately 80-85% of military accidents are the result of human error, stemming from cognitive performance errors (Thomas & Russo, 2007). Successful performance in operational and combat-specific tasks involves complex interactions between a soldier's cognitive skills and their physical capabilities that includes strength, power, and endurance, as well as their ability to effectively regulate force and power with optimal neuromuscular coordination and control to meet the imposed physical demands of various tasks (i.e., motor competence; MC) (Silvey et al., 2021; Terlizzi et al., 2022). In addition, Nindl and colleagues (2018) emphasize the importance of a soldier's ability to adapt to the imposed physical demands in "volatile, uncertain, complex, and ambiguous – VUCA" (p.1) operational contexts as a key factor for successful military performance. While assessing motor functioning and cognitive capabilities has a demonstrated history in military testing (Cecchini et al., 2021; McGrath et al., 2020; Weightman et al., 2015), their interconnectedness has not been fully appreciated.

MC-based experiences integrate the development of executive functions (EFs) via tactics, problem solving, exploration of physical and sociocultural environments, skill transfer, and continued adaptation of skills to meet context-specific demands of novel situations. Inhibition, working memory, and cognitive flexibility are three foundational EFs that support decision-making and problem-solving needed to adapt behaviors to achieve task-goals (Diamond, 2013). Researchers have also demonstrated a link between higher levels of cardiorespiratory fitness (CRF) and EF performance via increased brain volume (i.e., exercise-mediated neurogenesis) and formation of new blood vessels (i.e., angiogenesis) (Dupuy et al., 2015; Stein et al., 2018); however, evidence focusing on associations between EFs and learning/adaptability in complex movements in tactical athletes, is limited and warrants investigation.

The long-term processes associated with the acquisition and development of MC, specifically, effortful practice and performance of various locomotor and object control skills, provide direct mechanisms for contributing to EF development via different learning-related (e.g., synaptogenesis, hippocampal neurogenesis) as well as exercise-related (e.g., exercise-mediated neurogenesis, angiogenesis) mechanisms. Specifically, processes involved in the development of MC uniquely impacts EF via structural (i.e., the formation of new synapses; synaptogenesis) and functional (e.g., connectivity within and between neural networks) changes in the cerebellum (Diamond, 2000), basal ganglia (Leisman et al., 2014), hippocampus (Curlik et al., 2013), and prefrontal cortex (Diamond, 2000) that occur as a result of the multiple domains of learning involved in skill acquisition (Tomporowski & Pesce, 2019) and complex skill training (Ben-Soussan et al., 2015). In addition, the development of MC promotes the development of underlying strength and power attributes via enhancing inter-and intra-muscular coordination and control (e.g., motor unit recruitment, rate coding, synergistic muscle recruitment strategies) (Stodden et al., 2014), high levels of neuromuscular demand and also indirectly for developing cardiorespiratory fitness (via continued participation in activities inherently involving performance of various motor skills) (Cattuzzo et al., 2016). Thus, developing MC throughout childhood and adolescence directly and indirectly impacts EF through learning-related (e.g., synaptogenesis, hippocampal neurogenesis) and exercise-related (e.g., exercise-mediated neurogenesis, angiogenesis) mechanisms. However, current assessment methodologies used to assess the relationship between complex physical performance capabilities and cognitive performance in tactical athletes (i.e., soldiers) may not be sufficient (Hulteen et al., 2022).

Conventional, “integrated” motor and cognitive assessments have generally involved dual-task paradigms that embed classical EF tasks into non-complex movement tasks (e.g., performing a static balance while completing a number discrimination task; McGrath et al., 2020). Limitations in these assessment paradigms result in decontextualized tasks, therefore limiting the predictive utility of current dual-task assessments on soldiers’ motor and cognitive abilities as they do not consider soldiers’ MC skill levels and their importance in overall performance execution. For example, individuals with a broad foundation of MC skills will have a greater repertoire of movement options for effectively performing and adapting their movements during task execution based on changing task constraints (i.e., responding to dynamic environments, initial execution errors, or inappropriate initial movement choices) (Hulteen et al., 2022).

Recently, novel assessments have been developed using more contextualized tasks involving increased motoric complexity (e.g., Run-Roll-Aim, Instrumented Stand and Walk, Weightman et al., 2015; The Portable Warrior Test of Tactical Agility, Cecchini et al., 2021); however, differentiation of soldiers’ MC skill levels in these assessments is still lacking. Dual-task paradigms that empower individuals to autonomously manipulate MC and EF task complexity by choosing whether or not they adapt their performance (i.e., cognitively choosing a different potential motor solution during execution) offers an alternative way to concurrently examine MC and EF skills (Hulteen et al., 2022). For example, individuals with lower MC skill levels generally take longer to execute movement tasks and thus, do not have the capability to execute dual-task assessments quickly without increasing error (i.e., a speed-accuracy tradeoff). This lack of an individual's skill repertoire in both the speed of movement, as well as the lack of ability to adapt their performance, will result in increased time necessary to execute (i.e., slower task response time) and a decreased capability (i.e., lower MC skill and associated repertoire of movement options) to create effective and alternative solutions to problems. In addition, dual-task paradigms that include multiple complex tasks that inherently allow adaptability in MC and EF task complexity may more effectively elucidate decrements in MC, EF, or both capacities via an inability to adapt tactics (e.g., prioritizing one task over another, shifting attention between tasks too frequently) to improve performance and decrease the time to meet the task demands under different environmental conditions and contexts.

Motor-cognitive dual-task assessments that promote adaptability in skill performance and allow decision-making may more effectively capture cognitive involvement, and thus capabilities, across various MC tasks. Thus, the purpose of this study is to examine performance levels in object projection (throwing speed vs throw-catch), locomotor (linear hop vs six-meter crossover hop), and functional coordination (supine-to-stand vs supine timed up-and-go) skills that represent different levels of task complexity within a convenience sample of Army Reserve Officer Training Corps (AROTC) Cadets and compare the predictive utility of performance in these skills with individual and composite EF performance, controlling for CRF levels.

3.2 Methods

Participants and Setting

We recruited a convenience sample of Army Reserve Officer Training Corps (AROTC) Cadets from a program at a large university in the Southeastern United States. Prior to conducting the study, we obtained informed consent from all Cadets and approval from the human subjects' review board at the university.

Procedures

Cadets that volunteered for the study completed informed consent and the Physical Activity Readiness Questionnaire (Adams, 1999) to determine eligibility. Cadets who were under the care of a physician due to medical conditions (e.g., cardiac, pulmonary, musculoskeletal injury, concussion, pregnancy, chronic illness) that prevent them from physical activity or limit screen time were excluded from the study. Cadets completed MC, two-mile run, and EF testing across three weeks (one week per assessment) during normal AROTC physical training (6:00-7:00am). Trained research staff led the Cadets through a ten-minute general warmup that included dynamic stretching, lateral lunges, and light jogging prior to MC and EF testing sessions.

Instrumentation

Motor Competence (MC) Assessments

Traditional MC (T-MC) tasks were assessed by product-oriented measures which are sensitive discriminators of MC (Logan et al., 2017; Nesbitt et al., 2018; Stodden et al., 2009; Stodden et al., 2014). We used the T-MC skills and inspiration from tasks common in other domains (e.g., athletic training, physical therapy, strength and conditioning) to increase the complexity of each T-MC task and create higher complexity MC (HC-MC) which will also be assessed by product-oriented measures.

Traditional Motor Competence Tasks

Standing Long Jump. This assessment measures a Cadet's ability to explosively translate their center of mass using two feet. Starting with toes at the edges of the zero-distance mark, Cadets jumped forward as far as possible landing on both feet. The distance between the start line and the back of the heel closest to the start line was measured to the nearest centimeter and recorded as the distance jumped. Each Cadet completed three trials and the best score (i.e., the furthest jump) was used for data analysis (Stodden et al., 2009).

Supine-to-Stand. This assessment measures a Cadet's ability to coordinate their body effectively and efficiently to stand as quickly as possible from a supine position. Cadets started in the supine position with their hands by their side on a yoga mat with their feet in line with the edge of the mat. When given the "go" command, Cadets stood as quickly as possible and touched a designated spot on the wall in front of them (relative to shoulder height). No instructions were given to the Cadets on how to stand. Time between the "go" command and the Cadet touching the designated spot on the wall was recorded using a stopwatch. Cadets completed three trials and the fastest time was used for data analysis (Nesbitt et al., 2018).

Hopping. This assessment measures a Cadet's ability to translate their center of mass in a linear direction. Cadets hopped as quickly as possible over a distance of six meters on a linear path delimited by two lines taped on the floor (start and finish lines). The amount of time between the Cadet's hip crossing the start line and finish line was recorded using a stopwatch. Cadets completed two trials per leg, for a total of four trials and the fastest time was recorded and used for data analysis (Stodden et al., 2009).

Throw Speed. This assessment measures the Cadets ability to explosively project an object with maximum effort. Cadets threw a tennis ball (6.6 cm in diameter; weight 56g) with "maximum effort" toward a wall from an approximate distance of six meters. Peak ball velocity was measured using a radar gun (Stalker Pro II, Stalker Inc., Richardson, TX). Cadets completed three trials and the highest peak velocity was used for data analysis (Stodden et al., 2006a, 2006b).

Higher Complexity Motor Competence Tasks

Standing Triple Jump. This assessment challenges the Cadet to balance two competing goals, 1) distance per jump, 2) speed to optimize distance traveled as quickly as possible within the same locomotor skill (i.e., jumping) to maximize performance. On the "go" command Cadets jump forward three consecutive times "as far as possible and as quickly as possible." The distance between the start line and the back of the heel closest to the start line was measured to the nearest centimeter and recorded as the distance jumped. The amount of time between the "go" command and the third landing were also recorded for each trial. Each Cadet completed three trials and the maximum speed (i.e., distance divided by time) was used for data analysis.

Supine-timed Up and Go. This assessment provides Cadets with the cognitively challenging task of choosing movement solutions (how to most optimally stand) for manipulating their body positioning for maximum acceleration/deceleration at multiple stages (stand, accelerate/decelerate to and around the cone) of the task with a time constraint (Okely et al., 2021). Cadets started in the supine position with their hands by their side on a gymnasium floor with their feet in line with the start/finish line marked on the floor. When given the "go" command, Cadets stood as quickly as possible and sprinted 10 meters to a cone, maneuvered around the cone, then sprinted an additional 10 meters back through the starting line. No instructions were given to the Cadets on how to stand. The amount of time between the "go" command and the Cadet's hip crossing the start/finish line were recorded. If the cadet fell or slipped, that trial was voided, and they repeated the attempt. Cadets completed three trials and the fastest time was used for data analysis.

Six-meter Crossover Hop. This assessment provides the Cadet with the cognitively challenging tasks of balancing two competing goals, 1) speed (linear displacement), 2) accuracy (lateral displacement) within a single locomotor skill (i.e., hopping) to maintain postural control and maximize performance. Cadets traveled a total distance of six meters while hopping both linearly and laterally across two parallel lines 15cm apart as quickly and accurately as possible. The amount of time between the Cadet's hip crossing the start line and finish line was recorded. If a Cadet fell, touched the ground with the non-hopping foot, or did not fully hop over the two parallel lines (e.g., landed in-between lines or touched the lines), that trial was voided, and they repeated the attempt. Cadets completed two trials per leg, for a total of four trials and the fastest time, regardless of leg, was recorded and used for data analysis (Reid et al., 2007).

Throw-Catch. This assessment measures a Cadets ability to project and receive an object while providing the cognitively challenging task of continuously adjusting performance throughout the duration of the task. Cadets were asked to throw and catch a standard tennis ball (6.6 cm diameter, 56g) against the wall as many times as possible in 30 seconds. A score was awarded based on the number of successful throw and catch sequences completed during the 30-second trial. Throw-catch sequences were deemed successful if: 1) the ball was thrown from a position with both feet behind the tapeline (located at 3x standing height) and struck the wall in the air with no bounce, 2) the ball was caught in the air without contacting any body part other than the performer's hand(s) from a position with both feet behind the tapeline. Each Cadet completed two 30-second trials of the throw-catch task and the maximum score was used for data analysis (Terlizzi et al., 2022).

Executive Function Assessments

We programmed a battery of executive function tests using PsychoPy 2.2.2 (Peirce et al., 2019). Cadets completed the EF assessment battery on their personal computers with testing lasting approximately 30 minutes. Testing included the use of only two keys on the keyboard to minimize the influence of keyboard skills on performance. Each test was preceded by a standardized instruction display, and 20 practice trials per condition with feedback.

Color-Shape Switch Task. The color-shape switch task involves processing target stimuli in accordance with a frequently changing series of task responses which provides a global measure of cognitive control (Sicard et al., 2020). The switch task includes two conditions: homogeneous, which is comprised of two test blocks (color and shape), and heterogeneous. In the color test block, the Cadet responds by pressing buttons on the keyboard according to the color of the stimulus. In the shape test block, the Cadet responds by pressing buttons on the keyboard according to the shape of the stimulus. After completing the homogenous condition, each Cadet completes the heterogeneous condition during which they will be asked to alternate their responses between the homogeneous rule sets (color vs shape) according to the outline (either solid or dashed) of the stimuli. Stimuli were presented on the screen in a randomized sequence for 2000ms each, with an inter-stimulus interval of 50ms. Cadets were instructed to attend to the screen and respond accordingly using the "A" or "L" keys on their keyboard. Participants completed one block of 64 homogenous trials and three blocks of 64 heterogeneous trials for a total of 194 heterogeneous trials. Responses outside a time window of 2000ms after stimulus onset were considered as 'incorrect'. We calculated mean reaction time, response accuracy, errors of omission (misses) and errors of commission (false alarms) for each condition of the task. We calculated and used local reaction time switch cost (switch – non-switch trials) for data analysis.

N-Back Task. The n-back task is a series of tests developed to systematically measure an individual's working memory capacity by incrementally increasing cognitive demands such as; 1- and 2-back conditions (Sicard et al., 2018). Within each condition, a series of stimuli (letters) appear, and the Cadet is asked to indicate whether the target object is the same as the trial before (1-back), or the same as two trials before (2-back). White letters were presented in a randomized sequence on a black background for 500ms each. Inter-stimulus interval was 1,500ms. Cadets completed two blocks of 75 + *n* trials per condition. We omitted trials where no n-back response could be given (e.g., first two trials of each block in the 2-back) for a total of 150 trials per condition. Cadets were instructed to press the "A" key if the stimulus matched the stimulus *n* trials ago. Otherwise, the Cadet pressed the "L" key. Cadets were provided a self-determined pause for up to 5 minutes between blocks. We calculated mean reaction time, response accuracy, errors of omission (misses) and errors of commission (false alarms) for each condition of the task. We calculated and used d' (Z(hit rate) – Z(false alarm rate)) scores from the 2-back condition for data analysis

Modified Flanker Task. The flanker task employs multiple gradations of stimulus and response conflict. This task requires individuals to inhibit task-irrelevant information in order to correctly respond to a centrally presented target stimulus amid either congruent (<<<<<) or incongruent (<<><<) flanking stimuli. The incongruent condition, relative to the congruent condition, requires greater amounts of interference control (attentional inhibition) to ignore flanking stimuli, as concurrent activation of both the correct response (elicited by the target) and the incorrect response (elicited by the flanking stimuli) occurs before stimulus evaluation is complete (Kramer et al., 1994; Kramer & Jacobson, 1991; Spencer & Coles, 1999). Stimuli were randomly presented in white text on a black background for 200ms.

We randomized the inter-stimulus interval between 1,300 – 1,700ms (Moore et al., 2016) with a response window of 1650ms. Cadets completed two blocks of 76 trials for a total of 152 trials per condition. Cadets were instructed to press the key corresponding to the direction of the centrally presented target stimulus. For example, on compatible trials, the Cadet would press the "A" key when presented with the following stimulus (>><>>). To minimize testing fatigue, Cadets were provided a self-determined pause for up to 5 minutes between blocks. We calculated mean reaction time, response accuracy, median post-error reaction time and coefficient of variation in reaction time (CVRT) for each condition of the task. We calculated and used median post-error reaction time for the incompatible trial in our data analysis.

Cardiorespiratory Fitness

Two-Mile Run (2MR). Cadets completed the two-mile run test which has strong validity and reliability for estimating VO2 max in young adults in a military population (Mello et al., 1987; Sporiš, 2013; Walker et al., 2009). The Cadet's time was converted into an estimated VO_2 max according to gender using equations from US Army guidelines (Mello et al., 1987; Physical Fitness Training, 1992).

Data Analysis

We conducted an a priori power analysis using a small effect size (r =.35; Maurer & Roebers, 2019), alpha of .05, and power of .80, with the R package '*pwr*' (version 1.3-0) and estimated a minimum sample size of $N = 61$ was needed to investigate the overall relationship between MC and EFs for this study (i.e., not for gender-specific comparisons). Outlier trials for EF assessments were eliminated from reaction time data using an a-priori ± 2.5 SD criterion, within each participant for each variable. EF assessment data were then averaged across repetitions, again within each participant for each variable. Participants with an overall accuracy proportion < 0.55 on any test were classified as random performers and were excluded from further analyses.

First, we calculated descriptive statistics for T-MC, HC-MC, and EF tasks scores for the overall sample and by gender. EF performance scores were standardized into Z-scores and summed to create composite scores of EF. Second, we calculated Pearson's bivariate correlations (by total sample and by gender) evaluate the associations between raw scores in each of the T-MC and HC-MC with EF composite scores. Correlations of r = 0.40 – 0.59 were classified as moderate associations and $r \geq 0.60$ were classified as strong (Hall & Getchell, 2014). Third, we conducted two hierarchical regressions to assess the predictive utility of MC skill performance in T-MC and HC-MC tasks (independent variables) to EF composite scores (dependent variable) while controlling for CRF level and gender to examine the unique contributions of MC to EF performance. In addition, we conducted four gender-specific hierarchical linear regressions, controlling for CRF level to evaluate the effect of T-MC and HC-MC tasks on EF composite scores separately for men and women. Finally, we conducted ANOVAs on each of the total sample hierarchical regressions (T-MC and HC-MC) to determine if each successive step within each model is significant above and beyond the previous step in the model (Gelman, 2005). Residual plots from each model were visually inspected to ensure no obvious deviation from homoscedasticity or normality. We conducted all analyses using the statistical software R, version 4.1.3 (R Core Team, 2022) and implemented an alpha level of $p < .05$ to determine statistical significance.

3.3 Results

Overall, 83 Cadets volunteered both motor and cognitive testing for this study. We removed 24 Cadets who did not score above 55% correct across all cognitive tests. Resulting in a final sample of 59 participants (females *N* = 10 [16.9%], M_{age} = 22.67, SD_{age} = 4.60, range = 19 - 37; males *N* = 49 [83.1%], M_{age} = 22.49, SD_{age} = 3.25, range = 19 - 34) with a mean age of 22.54 years (*SD* = 3.61, range = 19-37) consisting of 5.1% African American, 1.7% American Indian, 5.1% Asian/Pacific Islander, 50.8% Caucasian, 6.8% Hispanic, with 30.5% of participants not reporting their ethnic background (*n* = 18). Females represented 16.9% of our sample, which is greater than the 15% representation of females in the U.S. Army (Dever, 2019).

Table 3.1 Exclusion of Participants

Reason:	Random Performance
Total	24 (28.9%)
Female	8 (44.4%)
Male	16 (24.6%)

Total Sample

T-MC assessments demonstrated weak correlations with EF composite scores (*r* = 0.167 – -0.286) with the supine-to-stand (*r* = -0.286) and hop (*r* = -0.264) demonstrating the strongest correlations among T-MC assessments. HC-MC assessments demonstrated weak to moderate correlations with EF composite scores (*r* = -0.171 – -0.434) with the six-meter crossover hop (*r* = -0.434) and throw-catch (*r* = 0.280) demonstrating the strongest correlations among HC-MC assessments (see Table 3.2 for EF behavioral data; see Table 3.3 for correlations). T-MC demonstrated weak correlations in males (*r* = .076 – -.121) and moderate correlations in females (*r* = .446 – .548) with EF composite scores (see Tables 3.4-3.5). HC-MC demonstrated weak to moderate correlations in males (*r* = .183 – -.308) and weak to moderate correlations in females (*r* = -.255 – -.523) with EF composite scores (see Tables 3.4-3.5).

Table 3.2 Cadets' Behavioral Performance on Executive Function Tasks (± 1 *SD*)

Measure		Females (*n* = 10)	Males (*n* = 49)	Total (*n* = 59)
Color-Shape Switch				
	Homogeneous RT	538.40 (± 107.01)	512.68 (± 94.74)	517.04 (± 96.43)
	Heterogeneous RT	1014.67 (± 180.48)	990.92 (± 219.17)	994.95 (± 211.87)
	Non-switch RT	984.27 (± 188.48)	944.78 (± 202.73)	951.47 (± 199.37)
	Switch RT	1045.80 (± 194.84)	1026.57 (± 237.52)	1029.83 (± 229.41)
	Global switch cost RT	476.27 (± 207.95)	478.24 (± 227.17)	477.91 (± 222.30)
	Local switch cost RT	61.53 (± 126.22)	81.79 (± 78.34)	78.36 (± 87.24)
	Working memory cost RT	445.87 (± 200.84)	432.09 (± 211.21)	434.43 (± 207.86)
	Homogeneous ACC	93.9 (± 10.0)	95.8 (± 7.0)	95.5 (± 7.5)
	Heterogeneous ACC	77.3 (± 14.1)	74.5 (± 14.2)	75.0 (± 14.1)
	Non-switch ACC	78.9 (± 17.0)	76.9 (± 15.0)	77.2 (± 15.2)
	Switch ACC	75.8 (± 12.7)	72.8 (± 14.2)	73.3 (± 13.9)
	Global switch cost ACC	16.7 (± 14.1)	21.3 (± 15.2)	20.5 (± 15.0)

	Local switch cost ACC	3.1 (± 6.9)	4.1 (± 6.8)	3.9 (± 6.8)
	Working memory cost ACC	15.0 (± 16.2)	18.9 (± 15.5)	18.3 (± 15.5)
N-back				
	1-Back RT	599.03 (± 103.73)	529.48 (± 83.03)	541.27 (± 89.82)
	2-Back RT	703.19 (± 213.59)	596.74 (± 149.98)	614.79 (± 165.28)
	1-Back ACC	85.1 (± 7.6)	86.4 (± 6.9)	86.2 (± 7.0)
	2-Back ACC	64.9 (± 15.0)	70.3 (± 11.8)	69.4 (± 12.5)
	N-back overall ACC	75.1 (± 9.2)	78.4 (± 8.4)	77.8 (± 8.6)
	1-Back *d′*	2.1 (± 0.7)	2.2 (± 0.7)	2.2 (± 0.7)
	2-Back *d′*	0.8 (± 0.8)	1.1 (± 0.8)	1.0 (± 0.8)
	N-back overall *d′*	1.4 (± 0.6)	1.6 (± 0.7)	1.5 (± 0.7)
Flanker				
	Compatible RT	544.67 (± 81.26)	452.80 (± 75.60)	468.37 (± 83.45)
	Incompatible RT	529.46 (± 82.87)	456.64 (± 83.40)	468.98 (± 87.07)
	Congruent RT	507.36 (± 62.49)	434.97 (± 64.11)	447.24 (± 68.98)
	Incongruent RT	568.84 (± 104.24)	474.26 (± 87.67)	490.29 (± 96.58)
	Overall RT	537.07 (± 77.83)	454.72 (± 74.37)	468.68 (± 80.55)

Compatible ACC	85.4 (± 13.5)	84.5 (± 10.4)	84.6 (± 10.9)
Incompatible ACC	83.2 (± 13.6)	83.5 (± 10.4)	83.4 (± 10.9)
Congruent ACC	87.3 (± 13.1)	89.7 (± 8.5)	89.3 (± 9.3)
Incongruent ACC	81.6 (± 14.0)	78.4 (± 11.7)	78.9 (± 12.0)
Overall ACC	84.2 (± 13.0)	84.0 (± 9.5)	84.0 (± 10.1)
Compatible post-error median RT	520.56 (± 89.77)	450.82 (± 81.68)	462.64 (± 86.42)
Incompatible post-error median RT	521.51 (± 87.15)	461.14 (± 91.63)	471.37 (± 93.00)
Congruent post-error median RT	491.16 (± 71.74)	446.29 (± 88.08)	453.25 (± 86.74)
Incongruent post-error median RT	563.43 (± 111.94)	473.27 (± 85.38)	488.55 (± 95.61)

Note: Values in RT rows are in milliseconds and values in ACC are percentages. RT = Reaction Time; ACC = Accuracy

Table 3.3 Correlations Between Skills of Traditional and Higher Complexity and Executive Functions (*N* = 59)

	M	*SD*	Local *RT* Switch Cost		2-Back *d′*		Incompatible Post-Error Median *RT*		EF Composite	
Lower Complexity										
SLJ (cm)	209.56	30.99	.037	[-.22, .29]	.141	[-.12, .29]	-.106	[-.35, .15]	.167	[-.09, .41]
Hopping (m/s)	2.03	0.34	-.043	[-.30, .22]	-.252	[-.48, .00]	.153	[-.11, .39]	-.264*	[-.49, -.01]
Throwing (mph)	54.54	12.33	.007	[-.25, .26]	.170	[-.09, .41]	-.239	[-.47, .02]	.245	[-.01, .47]
STS (s)	1.59	0.18	-.195	[-.43, .06]	-.219	[-.45, .04]	.071	[-.19, .32]	-.286*	[-.51, -.03]
Higher Complexity										
TJ (m/s)	2.89	0.59	.244	[-.01, .47]	-.004	[-.26, .25]	-.164	[-.40, .10]	.238	[-.02, .47]
X-Hop (s)	1.90	0.38	-.193	[-43., .07]	-.295*	[-.51, -.04]	.248	[-.01, .47]	-.434**	[-.62, -.20]
T&C (score)	13.42	2.95	-.002	[-.26, .25]	.216	[-.04, .45]	-.262*	[-.49, -.01]	.280*	[.03, .50]

S-TUG (s)	6.81	0.50	-.153	[-.39, .11]	-.209	[-.44, .05]	-.073	[-.32, .19]	-.171	[-.41, .09]

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*Note: *p < .05, **p < .01.* SLJ = Standing Long Jump; STS = Supine-to-Stand; TJ = Triple Jump; X-Hop = Six-meter Crossover Hop; T&C = Throw and Catch; S-TUG = Supine Timed up-and-go.

Table 3.4 Correlations Between Skills of Traditional and Higher Complexity and Executive Function Metrics in Male Cadets (*n* = 49)

	M	*SD*	Local *RT* Switch Cost		2-Back *d'*		Incompatible Post-Error Median *RT*		EF Composite	
Lower Complexity										
SLJ (cm)	217.90	25.16	-.158	[-.42, .13]	.036	[-.25, .31]	.027	[-.26, .31]	-.083	[-.36, .20]
Hopping (m/s)	1.94	0.26	.019	[-.26, .30]	-.135	[-.40, .15]	-.041	[-.32, .24]	-.048	[-.33, .24]
Throwing (mph)	57.43	11.16	-.078	[-.35, .21]	.079	[-.21, .35]	-.115	[-.38, .17]	.076	[-.21, .35]
STS (s)	1.55	0.16	.030	[-.25, .31]	-.256	[-.50, .03]	-.035	[-.31, .25]	-.121	[-.39, .17]
Higher Complexity										
TJ (m/s)	3.01	0.53	.068	[-.22, .34]	-.076	[-.35, .21]	-.150	[-.41, .14]	.084	[-.20, .36]
COD Hop (s)	1.79	0.30	-.138	[-40., .15]	-.204	[-.46, .08]	.168	[-.12, .43]	-.308*	[-.54, -.03]
T&C (#)	13.90	2.78	.031	[-.25, .31]	.123	[-.16, .39]	-.144	[-.41, .14]	.183	[-.10, .44]

S-TUG (s)	6.68	0.43	.079	[-.21, .35]	-.229	[-.48, .06]	-.154	[-.42, .13]	-.004	[-.28, .28]

*Note: *p < .05, **p < .01.* SLJ = Standing Long Jump; STS = Supine-to-Stand; TJ = Triple Jump; X-Hop = Six-meter Crossover Hop; T&C = Throw and Catch; S-TUG = Supine Timed up-and-go.

Table 3.5 Correlations Between Skills of Traditional and Higher Complexity and Executive Function Metrics in Female Cadets (*n* = 10)

	M	*SD*	Local *RT* Switch Cost		2-Back *d′*		Incompatible Post-Error Median *RT*		EF Composite	
Lower Complexity										
SLJ (cm)	168.70	24.11	.454	[-.25, .84]	.375	[-.33, .81]	.207	[-.49, .74]	.446	[-.26, .84]
Hopping (m/s)	2.5	0.29	.010	[-.62, .64]	-.690*	[-.92, -.11]	.194	[-.50, .73]	-.459	[-.84, .24]
Throwing (mph)	40.4	6.90	.107	[-.56, .69]	.569	[-.09, .88]	-.324	[-.79, .38]	.548	[-.13, .88]
STS (s)	1.76	0.16	-.848**	[-.96, -.47]	.154	[-.53, .71]	-.103	[-.69, .56]	-.515	[-.86, .17]
Higher Complexity										
TJ (m/s)	2.31	0.57	.737*	[.20, .93]	-.004	[-.63, .63]	.386	[-.32, .82]	.370	[-.34, .81]
COD Hop (s)	2.40	0.38	-.277	[-77., .43]	-.613	[-.90, .03]	-.035	[-.65, .61]	-.523	[-.87, .16]
T&C (#)	11.10	2.81	-.259	[-.76, .44]	.521	[-.16, .87]	-.457	[-.84, .24]	.308	[-.40, .79]

S-TUG (s)	7.26	0.57	-.639*	[-.90, -.02]	.023	[-.62, .64]	-.446	[-.84, .26]	-.255	[-.76, .45]

*Note: *p < .05, **p < .01.* SLJ = Standing Long Jump; STS = Supine-to-Stand; TJ = Triple Jump; X-Hop = Six-meter Crossover Hop; T&C = Throw and Catch; S-TUG = Supine Timed up-and-go.

In the first hierarchical multiple regression model, gender contributed significantly to the regression model, $F_{(1,57)} = 4.33$, $p = .042$, and accounted for approximately 7.1% (95% CI: 0.00 – 0.22) of the variance in EF composite scores. Adding estimated VO_2 max in step two explained an additional 3.3% (95% CI: -0.05 – 0.12) of the variance in EF composite scores, however the change in R^2 was not significant, $F_{(2,56)} = 2.03$, $p = .16$. The addition of T-MC performance to the final regression model explained an additional 6.4% of the variation in EF composite scores and this change in R^2 was not significant, $F_{(6,52)} = 1.00$, $p = .414$. Together all six independent variables predicted 17% of the variance in EF composite performance with no significant predictors, final model – $R^2 = 0.167$, $F_{(6,52)} = 1.74$, $p = 0.129$ (Table 3.6).

In the second hierarchical multiple regression model, gender contributed significantly to the regression model, $F_{(1,57)} = 4.33$, $p = .042$, and accounted for approximately 7.1% (95% CI: 0.00 – 0.22) of the variance in EF composite scores. Adding estimated VO_2 max in step two explained an additional 3.3% (95% CI: -0.05 – 0.12) of the variance in EF composite scores, however the change in R^2 was not significant, $F_{(2,56)} = 2.36$, $p = .131$. The addition of HC-MC performance to the final regression model explained an additional 17.4% of the variation in EF composite scores and this change in R^2 was significant, $F_{(6,52)} = 3.19$, $p = .020$. Together all six independent variables predicted 28% of the variance in EF composite performance with the strongest predictor being six-meter crossover hop performance which uniquely explained 11% of the variance, final model – $R^2 = 0.280$, $F_{(6,52)} = 3.37$, $p = 0.007$ (Table 3.6).

Table 3.6 Total Sample Hierarchical Regressions of Motor Competence Assessments on Executive Function Composites

Predictor	*b*	*b* 95% CI [LL, UL]	sr^2	sr^2 95% CI [LL, UL]	Fit	Difference
T-MC						
(Intercept)	-0.99	[-2.03, 0.06]				
Gender (Male)	1.19^*	[0.04, 2.34]	.07	[.00, .22]		
					$R^2 = .071^*$	
					95% CI [.00, .22]	
(Intercept)	0.93	[-1.95, 3.81]				
Gender (Male)	1.49^*	[0.28, 2.70]	.10	[-.05, .24]		
Est. VO$_2$ Max	-0.05	[-0.11, 0.02]	.03	[-.05, .12]		
					$R^2 = .103^*$	$\Delta R^2 = .033$
					95% CI [.00, .25]	95% CI [-.05, .12]
(Intercept)	8.17	[-2.12, 8.46]				
Gender (Male)	0.87	[-0.69, 2.42]	.02	[-.05, .09]		

Est. VO$_2$ Max	-0.04	[-0.11, 0.02]	.03	[-.05, .10]		
Standing Long Jump	-0.01	[-0.04, 0.01]	.02	[-.04, .07]		
Hopping	-0.82	[-2.97, 1.32]	.01	[-.04, .05]		
Throwing Speed	0.02	[-0.03, 0.07]	.01	[-.03, .05]		
Supine-to-Stand	-2.21	[-5.40, 0.99]	.03	[-.05, .11]		
					R^2 = .167	ΔR^2 = .064
					95% CI [.00, .27]	95% CI [-.05, .18]
HC-MC						
(Intercept)	-0.99	[-2.03, 0.06]				
Gender (Male)	1.19*	[0.04, 2.34]	.07	[.00, .22]		
					R^2 = .071*	
					95% CI [.00, .22]	
(Intercept)	0.93	[-1.95, 3.81]				
Gender (Male)	1.49*	[0.28, 2.70]	.10	[-.05, .24]		
Est. VO$_2$ Max	-0.05	[-0.11, 0.02]	.03	[-.05, .12]		

					$R^2 = .103^*$	$\Delta R^2 = .033$
					95% CI [.00, .25]	95% CI [-.05, .12]
(Intercept)	3.17	[-6.12, 2.56]				
Gender (Male)	0.3	[-1.06, 1.66]	.00	[-.02, .03]		
Est. VO_2 Max	-0.07^*	[-0.13, -0.01]	.07	[-.04, .17]		
Triple Jump	0.02	[-0.86, 0.90]	.00	[-.00, .00]		
Six-meter X-Hop	-2.51^{**}	[-4.26, -0.76]	.11	[-.03, .25]		
Throw-Catch	0.04	[-0.11, 0.20]	.00	[-.02, .03]		
S-TUG	0.57	[-0.57, 1.71]	.01	[-.04, .06]		
					$R^2 = .280^{**}$	$\Delta R^2 = .177^*$
					95% CI [.03, .39]	95% CI [.01, .34]

Note. A significant b-weight indicates the semi-partial correlation is also significant. b represents unstandardized regression weights. sr2 represents the semi-partial correlation squared. LL and UL indicate the lower and upper limits of a confidence interval, respectively. Six-meter X-Hop = Six-meter Crossover Hop; S-TUG = Supine Timed Up-and-Go.
* indicates $p < .05$. ** indicates $p < .01$.

Males

In the first male hierarchical multiple regression model, estimated VO_2 max did not contribute significantly to the regression model, $F_{(1,47)} = 1.10$, $p = 0.298$, and accounted for approximately 2.3% (95% CI: 0.00 – 0.16) of the variance in EF composite scores. The addition of T-MC performance to the final regression model explained an additional 5.4% (95% CI: -0.07 – 0.18) of the variation in EF composite scores and this change in R^2 was not significant, $F_{(5,43)} = 0.63$, $p = 0.646$. Together all five independent variables predicted 7.7% (95% CI: 0.00 – 0.16) of the variance in EF composite performance with no significant predictors, final model – $R^2 = 0.077$, $F_{(5,43)} = 0.72$, $p = 0.616$ (Table 3.7).

In the second male hierarchical multiple regression model, estimated VO_2 max did not contribute significantly to the regression model, $F_{(1,47)} = 1.10$, $p = 0.298$, and accounted for approximately 2.3% (95% CI: 0.00 – 0.16) of the variance in EF composite scores. The addition of HC-MC performance to the final regression model explained an additional 16.6% (95% CI: -0.02 – 0.35) of the variation in EF composite scores and this change in R^2 was not significant, $F_{(5,43)} = 2.20$, $p = 0.085$. Together all five independent variables predicted 18.9% (95% CI: 0.00 – 0.31) of the variance in EF composite performance with the only significant predictor being six-meter crossover hop performance which uniquely explained 12% of the variance, final model – $R^2 = 0.189$, $F_{(5,43)} = 2.01$, $p = 0.097$ (Table 3.7).

Table 3.7 Hierarchical Regressions of Motor Competence Assessments on Executive Function Composites in Male Cadets (*n* = 49)

Predictor	*b*	*b* 95% CI [LL, UL]	sr^2	sr^2 95% CI [LL, UL]	Fit	Difference
T-MC						
(Intercept)	1.83	[-1.32, 4.99]				
Est. VO$_2$ Max	-0.03	[-0.10, 0.03]	.02	[.00, .16]		
					R^2 = .023	
					95% CI [.00, .16]	
(Intercept)	8.16	[-2.60, 18.93]				
Est. VO$_2$ Max	-0.03	[-0.10, 0.04]	.01	[-.05, .08]		
Standing Long Jump	-0.02	[-0.04, 0.01]	.03	[-.06, .13]		
Hopping	-0.52	[-2.92, 1.88]	.00	[-.03, .04]		

Throwing Speed	0.02	[-0.03, 0.07]	.01	[-.04, .07]		
Supine-to-Stand	-1.94	[-5.55, 1.66]	.03	[-.06, .11]		
					R^2 = .077 95% CI [.00, .16]	ΔR^2 = .054 95% CI [-.07, .18]
HC-MC						
(Intercept)	1.83	[-1.32, 4.99]				
Est. VO_2 Max	-0.03	[-0.10, 0.03]	.02	[.00, .16]		
					R^2 = .023 95% CI [.00, .16]	
(Intercept)	1.81	[-8.28, 11.90]				
Est. VO_2 Max	-0.05	[-0.12, 0.01]	.05	[-.06, .16]		
Triple Jump	-0.15	[-1.11, 0.81]	.00	[-.02, .02]		
Six-meter X-Hop	-2.55^{*}	[-4.57, -0.53]	.12	[-.04, .29]		
Throw-Catch	0.04	[-0.13, 0.22]	.00	[-.03, .04]		
S-TUG	0.79	[-0.50, 2.07]	.03	[-.06, .11]		
					R^2 = .189	ΔR^2 = .166

95% CI [.00, .31]	95% CI [-.02, .35]

Note. A significant b-weight indicates the semi-partial correlation is also significant. b represents unstandardized regression weights. sr2 represents the semi-partial correlation squared. LL and UL indicate the lower and upper limits of a confidence interval, respectively. Six-meter X-Hop = Six-meter Crossover Hop; S-TUG = Supine-Timed-up-and-Go.

* indicates $p < .05$. ** indicates $p < .01$.

Females

In the first female hierarchical multiple regression model, estimated VO_2 max did not contribute significantly to the regression model, $F_{(1,8)} = 3.87$, $p = 0.085$, and accounted for approximately 32.5% (95% CI: 0.00 – 0.63) of the variance in EF composite scores. The addition of T-MC performance to the final regression model explained an additional 33% (95% CI: -0.08 – 0.74) of the variation in EF composite scores and this change in R^2 was not significant, $F_{(5,4)} = 0.96$, $p = 0.517$. Together all five independent variables predicted 65.5% (95% CI: 0.00 – 0.71) of the variance in EF composite performance with no significant predictors, final model – $R^2 = 0.65$, $F_{(5,4)} = 1.52$, $p = 0.353$ (Table 3.8).

In the second female hierarchical multiple regression model, estimated VO_2 max did not contribute significantly to the regression model, $F_{(1,8)} = 3.87$, $p = 0.085$, and accounted for approximately 32.5% (95% CI: 0.00 – 0.63) of the variance in EF composite scores. The addition of HC-MC performance to the final regression model explained an additional 44% (95% CI: 0.01 – 0.87) of the variation in EF composite scores and this change in R^2 was not significant, $F_{(5,4)} = 1.88$, $p = 0.278$. Together all five independent variables predicted 76.6% (95% CI: 0.00 – 0.80) of the variance in EF composite performance with no significant predictors, final model – $R^2 = 0.766$, $F_{(5,4)} = 2.62$, $p = 0.186$ (Table 3.8).

Table 3.8 Hierarchical Regressions of Motor Competence Assessments on Executive Function Composites in Female Cadets (*n* = 10)

Predictor	*b*	*b* 95% CI [LL, UL]	sr^2	sr^2 95% CI [LL, UL]	Fit	Difference
T-MC						
(Intercept)	11.48	[-3.19, 26.15]				
Est. VO_2 Max	-0.30	[-0.65, 0.05]	.33	[.00, .63]		
					$R^2 = .326$ 95% CI [.00, .63]	
(Intercept)	18.67	[-47.60, 84.95]				
Est. VO_2 Max	-0.32	[-0.87, 0.23]	.23	[-.13, .59]		
Standing Long Jump	0.03	[-0.08, 0.14]	.04	[-.11, .19]		
Hopping	-2.49	[-13.89, 8.92]	.03	[-.10, .16]		
Throwing Speed	-0.05	[-0.55, 0.46]	.01	[-.05, .06]		
Supine-to-Stand	-1.56	[-15.24, 12.12]	.01	[-.06, .08]		
					$R^2 = .655$	$\Delta R^2 = .330$

					95% CI [.00, .71]	95% CI [-.08, .74]
HC-MC						
(Intercept)	11.48	[-3.19, 26.15]				
Est. VO$_2$ Max	-0.30	[-0.65, 0.05]	.33	[.00, .63]		
					R^2 = .326	
					95% CI [.00, .63]	
(Intercept)	20.97	[-18.45, 60.39]				
Est. VO$_2$ Max	-0.36	[-0.74, 0.02]	.41	[-.01, .84]		
Triple Jump	0.20	[-3.22, 3.61]	.00	[-.02, .02]		
Six-meter X-Hop	-2.85	[-7.64, -1.94]	.16	[-.11, .43]		
Throw-Catch	0.08	[-0.48, 0.64]	.01	[-.05, .07]		
S-TUG	-0.20	[-3.94, 3.54]	.00	[-.02, .02]		
					R^2 = .766	ΔR^2 = .440
					95% CI [.00, .80]	95% CI [.01, .87]

Note. A significant b-weight indicates the semi-partial correlation is also significant. b represents unstandardized regression weights. sr2 represents the semi-partial correlation squared. LL and UL indicate the lower and upper limits of a confidence interval, respectively. Six-meter X-Hop = Six-meter Crossover Hop; S-TUG = Supine-Timed-up-and-Go.
* indicates $p < .05$. ** indicates $p < .01$.

3.4 Discussion

This study examined the predictive utility of performance on motor skills with different levels of motoric complexity and their associations with EF performance. Skills with greater motoric complexity that require greater cognitive demands, demonstrated stronger associations with EF composite scores ($r = -.434 – .280$) compared to performance associated with more traditional skill assessments ($r = -.286 – .167$). In addition, HC-MC performance was a significant predictor of EF composite scores ($R^2 = 0.28$, $F_{6,52} = 3.37$, $p = 0.007$) when controlling for gender and CRF levels in this sample. These data provide preliminary evidence that when assessing the relationship between motor competence and executive functions, the level of gross motor complexity in assessments is an important factor to consider. When stratified by gender, neither the T-MC nor HC-MC models were significant, although the power to assess gender-specific associations was not adequate (males: $1\text{-}\beta = 0.68$; females $1\text{-}\beta = 0.66$). Our convenience sample was recruited based on an a priori power calculation for the entire sample and therefore this study was not sufficiently powered to detect effects between T-MC and HC-MC performance within gender. However, preliminary results demonstrated the HC-MC models explained more variance than T-MC models within males (HC-MC model – $\Delta R^2 = 0.166$, $p = 0.085$ vs T-MC model – $\Delta R^2 = 0.054$, $p = .646$) and females (HC-MC model – $\Delta R^2 = 0.44$, $p = 0.278$ vs T-MC model – $\Delta R^2 = 0.33$, $p = 0.517$). When examining potential contributions of individual HC-MC variables that were based on semi-partial correlations (see Tables 3.6-3.8), the six-meter crossover hop may have accounted for all unique contributions within the locomotor domain, thus we suggest removing the triple jump assessment from the HC-MC model to create a more parsimonious model (i.e., one assessment per MC domain;

[object control, locomotor, functional coordination]) for future investigations into HC-MC and EF performance.

Our results support previous evidence demonstrating a stronger association between motor skills with increased complexity and EF scores (Maurer & Roebers, 2019). This study uniquely contributes to the literature by promoting MC-EF assessment paradigms with a novel view of dual-task assessments that promotes decision-making and allows flexibility in skill performance characteristics (i.e., different skill levels) to enhance task performance. Individuals with an extensive repertoire of MC skills will have more movement options for effectively performing and adapting to dynamic environments (e.g., VUCA) during task performance.

In addition, our results also provide evidence demonstrating the impact of MC above and beyond CRF levels. Our sample included a potentially limited range of CRF levels as measured by estimated $VO_{2\ \max}$ (range = 30.55 – 60.40; *M* = 47.00; *SD* = 7.09), which may account for the demonstrated weak associations with EF composite scores ($r = -.077, p = .55$). Although previous physical activity—cognition research has demonstrated significant relationships between CRF and cognitive performance, the context of CRF development must be considered (Diamond & Ling, 2016; Haapala, 2013; Pesce, Vazou, et al., 2021). Exercise-related mechanisms support the development of EFs via angiogenesis and exercise-mediated neurogenesis (Stillman et al., 2016), but increases in CRF facilitated without sufficient cognitive engagement may be less impactful on EF development (Diamond & Ling, 2016; Pesce, Vazou, et al., 2021). AROTC training is designed to improve CRF which may skew these results as their approach does not account for the long-term concurrent development of EF and MC. Thus, providing individuals with perceptually rich and dynamic movement environments (which HC-MC tasks aim to represent) across time may play a more important role than the exercise-related mechanisms in the development of EFs via direct (learning-related) mechanisms. However, acute performance of complex locomotor and object projection/reception skills (Sacko et al., 2018; Sacko et al., 2019) and the associated activities inherently requiring adequate levels of multiple skill competence for sustained participation both contribute to the development of CRF from an exercise intensity perspective (i.e., metabolic equivalent for task – METs). Thus, promoting context-specific physical activities that include perceptually rich environments that facilitate continued learning as well as health-enhancing activity levels would be the most optimal setting for enhancing cognitive development.

While we acknowledge the development of previous dual-task assessments have advanced the field of military performance, this study has also demonstrated a potential critical need to advance current dual-task assessment approaches to align the underlying processes of motor and cognitive development. In essence, stronger associations with performances in HC-MC tasks, which provide higher levels of motoric and cognitive complexity call for dual-task assessments that effectively capture this relationship. The throw-catch task affords a perceptually rich environment that encompasses continuous decision-making by allowing individuals to modify their performance (either by throwing form, body position, or both) to effectively adjust their subsequent performance (i.e., next throws) to optimize performance throughout the duration of the task (see Figure 3.1 for associations with EF composite). Similarly, the six-meter crossover hop affords a perceptually rich and complex performance environment that embraces continuous decision-making by requiring individuals to prioritize both speed (linear displacement) and accuracy (lateral displacement) throughout the duration of the task (see Figure 3.2 for associations with EF composite). For example, if an individual hops too far laterally, they compromise their ability to quickly and efficiently move in a linear path which requires the individual to decrease their speed and adjust their path. The supine timed up-and-go task impacts decision-making by providing individuals with the cognitively challenging task of choosing movement solutions (how to most optimally stand) for manipulating their body positioning for maximum acceleration/deceleration at multiple stages (stand, accelerate/decelerate to and around the cone) of the task with a time constraint (see Figure 3.3 for associations with EF composite). Although there is a general belief by many that MC (coordination and control) in many skills is developed "naturally," the complexity inherent in its intransitive, sequential, and cumulative (Clark & Metcalfe, 2002) progression cannot be effectively established in acute training settings (e.g., 12 weeks of basic combat training); rather, the development of MC requires longer time scales with progressive training to effectively apply and adapt to various movement outcomes. In addition, MC-based experiences integrate the development of EFs via tactics, problem solving, exploration of physical and sociocultural environments, skill transfer, and continued adaptation of skills to meet context-specific demands of novel situations.

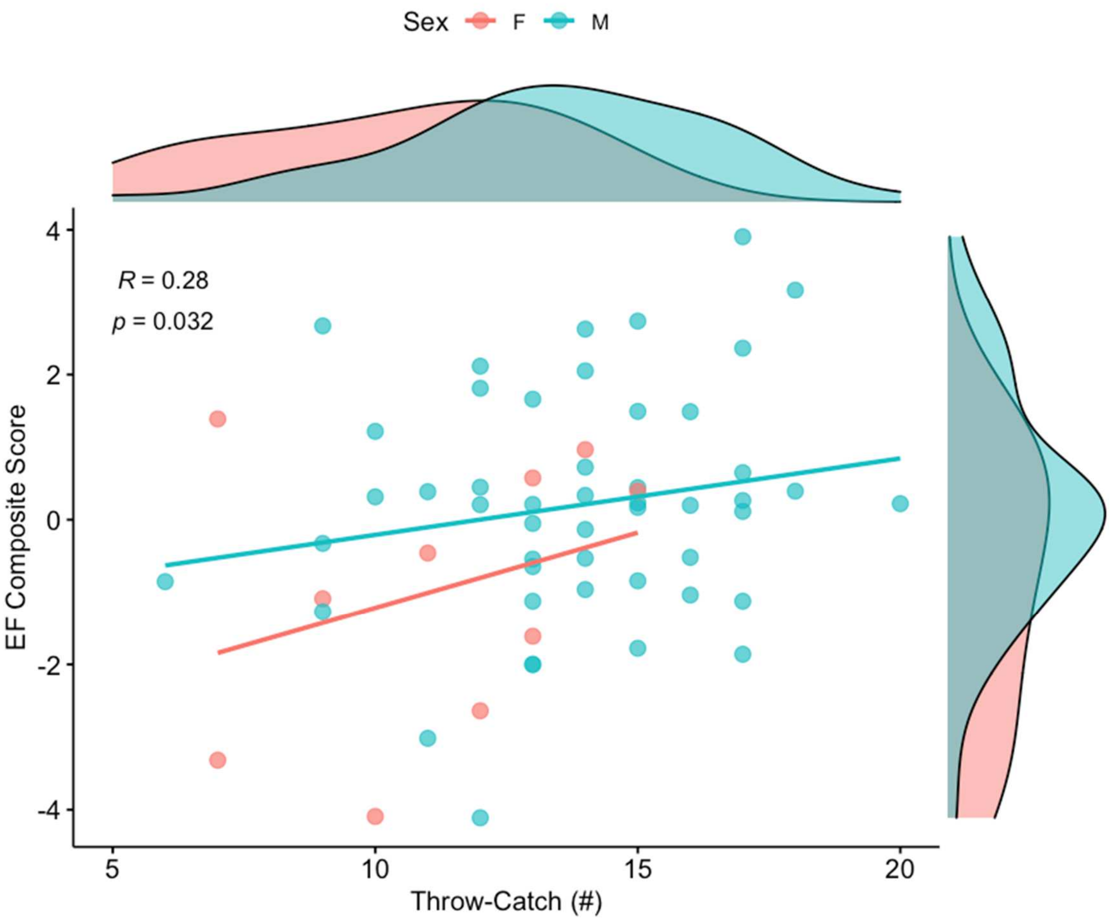

Figure 3.1 Scatterplot with Marginal Histograms of Throw-Catch Scores and Executive Function Composite Scores

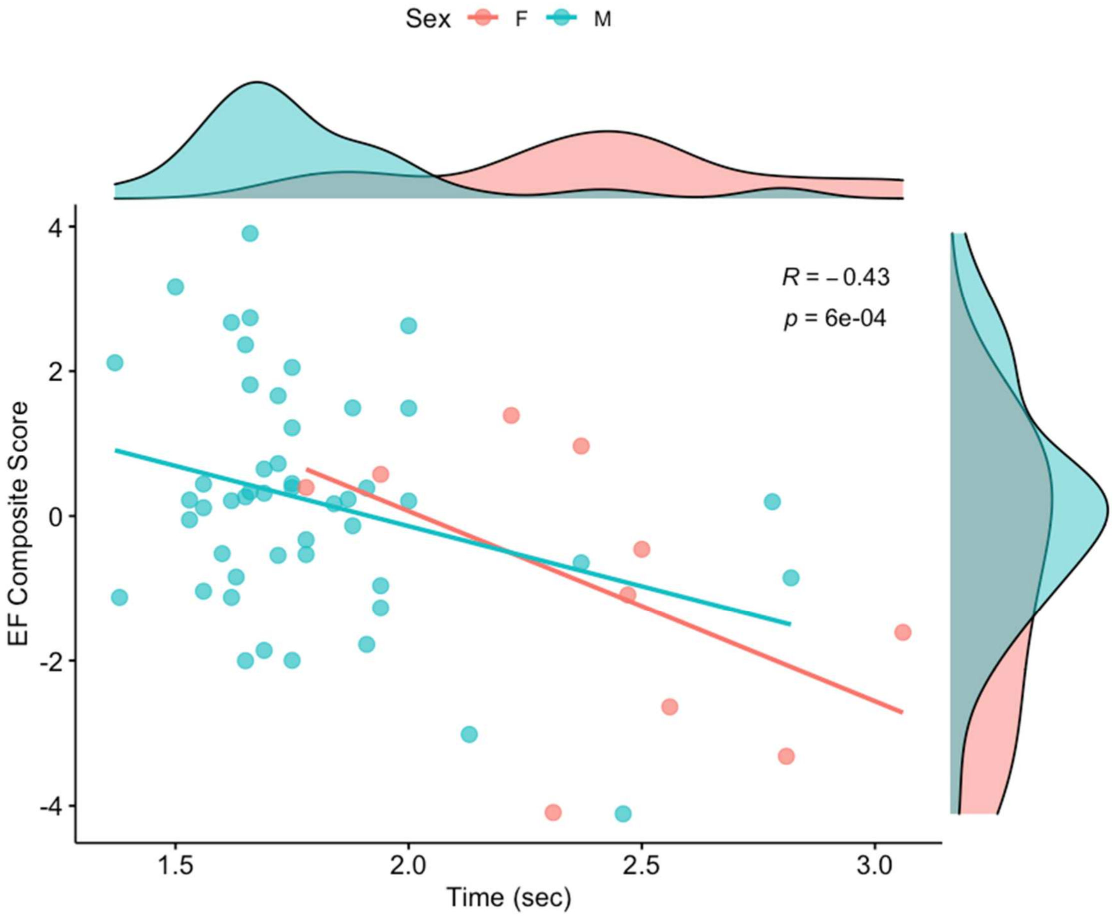

Figure 3.2 Scatterplot with Marginal Histograms of Crossover Hop Times and Executive Function Composite Scores

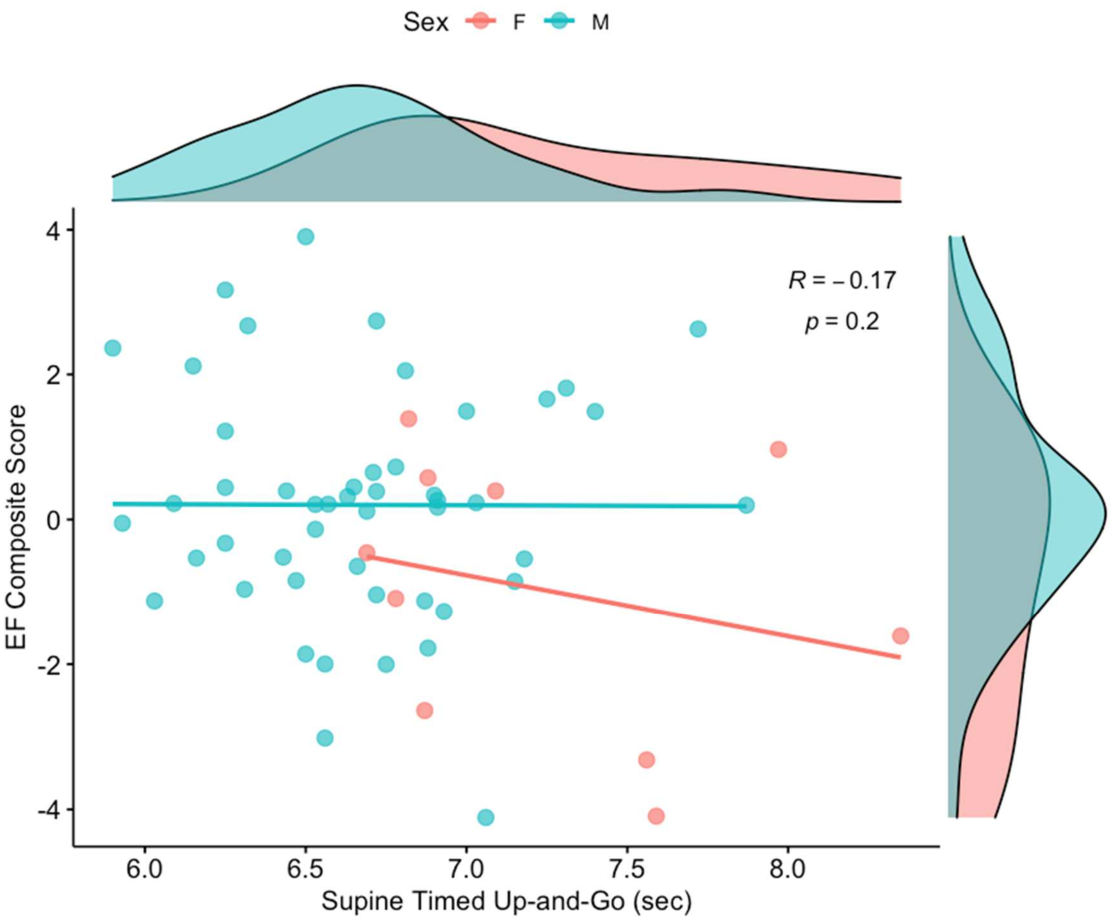

Figure 3.3 Scatterplot with Marginal Histograms of Supine Timed Up-and-Go Times and Executive Function Composite Scores

Limitations

The current study was limited in a few ways. First, the cross-sectional design only provides associational evidence for the potential impact of increased motor complexity assessments on EFs. It is difficult to adequately define differences in complexity levels between and among skills as the proposed "higher complexity" skill assessments are novel adaptations of traditional skill assessments (e.g., triple jump, crossover hop) or combinations of multiple skills that are performed in a unique environmental context (e.g., throw-catch, supine-timed-up-and-go). However, data generally demonstrate stronger associations between MC and EFs with assessments that require greater motoric complexity, flexibility, adaptability, and greater cognitive demands. Additional longitudinal and intervention studies will be needed to determine the impact that HC-MC development has on cognitive development. Second, our final study sample included a limited number of participants, however, the preliminary gender-specific HC-MC models explained a larger amount of variance than T-MC. Based on this preliminary data, future studies should investigate the differential relationships between gender, HC-MC performance, and EF composite scores with larger sample sizes. Third, this study indirectly measured $V0_{2\ \max}$ which limited our ability to accurately measure true CRF levels. In absence of directly measuring $V0_{2\ \max}$, we used gender-specific formulas specifically created for the two-mile run assessment which have demonstrated validity and reliability (Mello et al., 1984, 1987). Fourth, we did not report body mass index (BMI) data. We did not collect BMI information from our sample because of the strict BMI standards (e.g., males < 27.5; females < 26; Army, 2013, 2016) for continued participation in AROTC which generally results in a more homogenous body weight status population. Lastly, the results of this study were based on one sample of AROTC Cadets in the southeastern U.S. and further research is needed with larger sample sizes across multiple ROTC branches (e.g., Air Force, Navy, Marine Corps, Space Force, Army) in multiple locations within the U.S. to confirm our results.

Conclusion

Research examining the link between motor and cognitive performance traditionally embed classical EF tasks with non-complex movement tasks (T-MC). However, T-MC tasks may not sufficiently capture the learning- and exercise-related mechanisms by which the development of MC impacts and supports EFs due to restrictive performance environments and limited decision-making requirements. HC-MC tasks bridge this gap by examining the importance of differences in skill levels and by affording moment-to-moment adaptations to coordination patterns (i.e., continuous decision-making) and empowering individuals to regulate complex motoric and cognitive interactions within the individual-environment system via flexible and creative coordination patterns and strategies. A developmental approach to HC-MC assessment may help align underlying processes of motor and cognitive development by more effectively capturing the concurrent development of MC and EF across time. In addition, this novel view of dual-task assessments may lead to a better understanding of the impact that the development of MC has on holistic human performance in tactical athletes.

CHAPTER 4

CONCLUSION

This dissertation aimed to expand previous research in motor development and neuroscience by more effectively linking MC and EFs via assessments that inherently require increased levels of cognition and acknowledge the importance of the development of an individual's skill repertoire (i.e., skillfulness). These MC assessments align the underlying processes of motor and cognitive development. Specifically, HC-MC assessments promote an integrative approach to MC-EF paradigms with consideration to the complex interactions between learning and exercise-related mechanisms that concurrently impact motor and cognitive development. In addition, HC-MC assessments afford moment-to-moment adaptations to coordination patterns (i.e., continuous decision-making) and empower individuals to regulate complex motoric and cognitive interactions within the individual-environment system via flexible and creative coordination patterns and strategies. Recent assessments have noted the role of motoric complexity, which has demonstrated stronger associations with cognitive performance (Cecchini et al., 2021; Maurer & Roebers, 2019; Weightman et al., 2015); however, recognizing the MC skill level of an individual is still lacking. Our results indicate that assessments with increased motoric complexity and acknowledgement of an individual's skill repertoire provide greater predictive utility and stronger associations with measures of EFs than traditional MC assessments. Advancing MC assessments has implications for various fields (e.g., physical education, physical therapy, military performance) by providing a better understanding of how motor and cognitive processes are embedded and manifest across stages of development and continue to promote MC as a critical component for holistic human development.

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