SwitchedOn® Whitepaper

A Narrative Review on the Neuroscience of Athletic Performance & The Incorporation of Cognitive Demands into Agility Training

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Introduction

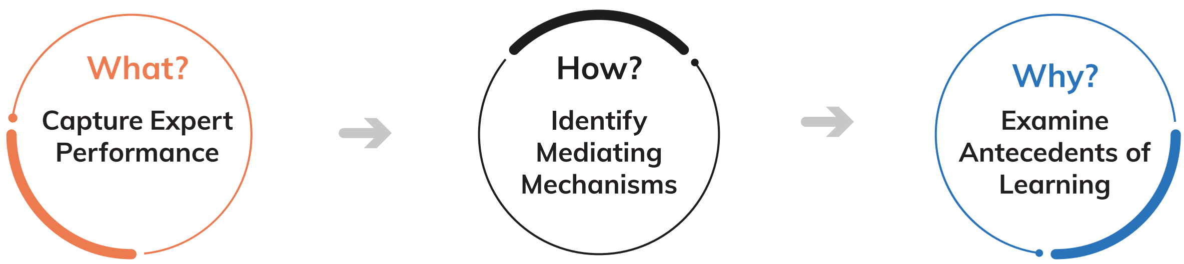
The intersection of neuroscience, sports science, and psychology has allowed for advances in understanding how the brain plays a role in athletic performance. While the interest in improving athletic performance is an age-old endeavor, recent advances in neuroscience and cognitive psychology have elucidated the potential in assessing and training the neurological systems, specifically the brain, of athletes in order to achieve greater improvements in sports performance. These potential applications range from improving sport skills, preventing injury, concussion rehabilitation, and athletic conditioning. While the emerging research is exciting, more research is needed to better understand what characteristics the brains of elite athletes possess and its relationship to sports performance. In addition, the emergence of training products targeting the brains of athletes require further evaluation to determine whether they truly transfer to sports environments, if their proposed mechanisms possess any scientific merit, and what characteristics such training approaches might require to increase their likelihood of effectiveness.

Understanding the Athlete's Brain

There is an increasing amount of mainstream interest in understanding the structural and functional properties of the brain's of elite athletes. There are various methods employed to study this, from using computerized or "pencil-and-paper" neuropsychological testing to measure performance of certain cognitive abilities, such as processing speed and attention, to using forms of neuroimaging, such as fMRI and QEEG. A combination of functional and structural neuroimaging, combined with the assessment of behavioral outcomes such as cognitive testing, paints a more detailed picture of what neural characteristics athletes possess that may underlie performance.

However, there are a wide variety of factors that likely influence these characteristics, including age, gender, socioeconomic status, geographic location, ethnicity, anthropomorphics, level of education, lifestyle factors, skill level, experience, fitness levels and the sport in question. Given these wide range of variables, it is challenging to replicate study protocols in a variety of these conditions within the current state of the literature, and therefore assumptions can only be drawn from existing literature until more research is published.

There are various approaches to understanding the cognitive abilities and behavior underlying athletic performance. The "Expert Performance Approach" seeks to examine how expert athletes perform in sport-specific or ecologically-valid environments (Williams, et al. 2017), whereas the "Cognitive Component Skill Approach" recognizes sport as a form of cognitive training that can improve domain-specific cognitive skills. The expert approach seeks to capture expert performance in one or more settings, attempts to identify mechanisms underlying performance, and finally examine what experiences or characteristics may have existed prior to the development (learning) associated with expertise in sport (Ford, et al. 2009). By better understanding the individual cognitive domains (or mental functions) that underlie sports performance, both general and specific, it is thought that these cognitive functions can be targeted to improve one or more aspects of sports-performance, although there are criticisms to this approach as it may lack sport-specificity in the absence of the complexities found in sporting environments (Voss, et al. 2010).



- Laboratory and field-tests
- Cotrolled and reproducible conditions
- Identify components of performance
- Expert-invoice paradigm
- Withing-task criterion
- Individuals differences

- Process-tracing measures
- Inductive and deductive identification of mechanisms
- Multi-measures approach
- Eye movement recording
- Think-aloud protocols
- fMRI, TMS, EEG, ERPs
- Kinematic and Kinetic measurement
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Figure 1. The experts performance approach proposed by Ericsson and Smith (1991). adapted from Williams and Ericsson

Sport, Skill & Cognition

Different modalities of sport consist of various characteristics that may influence specific neurological traits of athletes. When determining the cognitive traits of athletes, or when designing training programs, it is important to consider the nature of the sport in question. Such classifications include team sports (i.e. volleyball), invasion sports (i.e. football), striking sports (i.e. baseball), interceptive sports (i.e. tennis) and strategic sports (i.e. fencing). A way to further classify sports is to identify whether a skill is internally (self)-paced or externally-paced. Another way to identify these skills is as open-skill or closed-skill. Closed-skills typically include stable, repetitive and predictable movement patterns (i.e. swimming, running), whereas open-skills include unpredictable, constantly changing, and oppositional stimuli (i.e. soccer, tennis). It is thought that open-skill activities may differentially demand more of specific cognitive functions when compared to closed-skills, however both types of skills may improve cognition, either by directly acting on cognitive functions (as seen in open skills), or indirectly impacting the brain via energetic pathways (as seen in closed skills) (Nuri, et al. 2013, Elferink-Gemser, et al. 2018).

Cognition can be fractionated into various "sub-domains" of cognition that represent specialized mental functions, each of which possess specific structural and functional correlates in the central nervous system. In order to better understand these cognitive domains, it is helpful to classify how different types of stimuli may be processed by the brain. "Bottom-up" processing refers to simplistic stimuli that are organized by sensory systems and processed by lower-level cognition. "Top-down" processing is responsible for interpreting more complex information that is processed by higher-level cognition.

Attention is the ability to process relevant, goal-oriented information and ignore (or filter) irrelevant information unrelated to a goal (Tang, et al. 2009). Reaction time is used as a measure of time to gauge "the mental chronometry of shift of attention" (Voss, et al. 2010) within an environment's given relevant stimuli.

Attentional cues can either be processed via endogenous cueing (when information is provided about where a stimulus may appear, such as an arrow) or via exogenous cueing (when no information about a cue is given and attention is shifted reflexively) (Posner & Fan, 2008). Attentional cues can also be more complex, including selective attention paradigms (in which irrelevant stimuli must be suppressed) and divided attention paradigms (in which attention is split amongst multiple stimuli).

Processing speed can be measured by the efficiency of a physical response within tasks that require information processing, and is measured by reaction time. Processing speed has been identified as a marker associated with aging and development, and is likely to be necessary for both accurate and quick decision-making in fast-paced sporting environments. Processing speed can also be categorized depending upon the primary sensory system associated with the information processing, such as visual processing speed (stimuli processed via the visual system) or auditory processing speed (stimuli processed via the auditory system). Elite athletes seem to demonstrate superior performance on tasks that require processing speed and attention (Voss, et al. 2010).

Bottom-Up vs. Top-Down Processing

Whereas bottom-up processing includes basic forms of attention and processing speed, top-down processing includes more complex, higher-level cognitive functions. Executive functions (EFs) is an umbrella term that emcompasses a wide array of cognitive functions that are associated with more complex functions. These more complex functions are needed when there is deviation from predictable patterns, stimuli, or everyday routine (Miyake, et al. 2012). While there are many "sub-domains'' of executive functioning, there are three primary components of executive functions that have been identified by researchers. These domains include impulse control (suppressing or inhibiting responses), working memory (updating and monitoring temporarily-stored, continuous information), and shifting (switching attention between different tasks).

These executive functions (as referred to above) are also referred to as "cool" executive functions, since they refer to more complex cognitive processing. However, the brain is not only responsible for cognitive processes, but emotional processes, as well. Therefore, the process of emotional control and self-regulation also involves executive functions, and the management of these functions is referred to as "hot" executive functions. These "hot" EFs also may refer to processes such as impulse control under pressurized conditions with limited time (Holfelder, et al. 2020).

In studying expertise in sports, the classifications of open vs. closed skills, general vs. sport specificity, "hot" vs. "cool" executive functions, and simple vs. complex tasks may be compared and contrasted. This "four-dimensional approach" to classifying skill specificity allows for greater ease in classifying expertise without being limited to a single model or approach.

There are various studies that have begun to identify what cognitive traits athletes may possess at higher levels of performance, although some of these may be mediated by some of the aforementioned factors, such as age or the level of skill an athlete possesses. For example, in a study of football players, levels of executive functioning may be age dependent, as a plateau in higher-level cognitive functions is found at 21 years of age, which may reflect the development of the nervous system, more than enhancements in executive functioning as a result of training (Beavan, et al. 2020), although certain interventions at certain points in development may beneficially affect the trajectory, utility, and/or development of these cognitive skills. However, other studies in soccer players, for instance, found that higher levels of executive functions were predictive of athletic performance even when controlling for age and intelligence (Vestberg, et al. 2017).

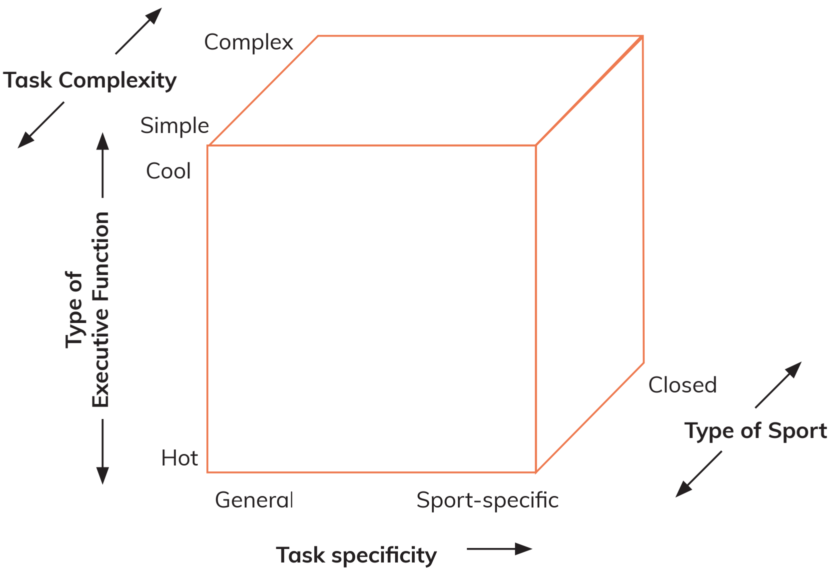


Figure 2: Proposed four-dimensional classification multicomponent system to examine expertise effects in sport (Holfelder, et al. 2020).

Cognition in High-Level Athletics

Identifying the neural and psychological mechanisms that underlie expert performance may allow professionals to trace how such skills are acquired and measured, and promote training in the acquisition of such skills (Ford, et al. 2009). One approach to designing and selecting interventions may include identifying what cognitive traits elite athletes may possess, and creating approaches that target those specific cognitive functions (Faubert, et al. 2012). However, a potential flaw to this approach is that the superior cognitive abilities found in certain athletes may be developed by way of improving sports performance by practicing the sport, rather than training in more generalized or artificially-created modalities, rather than more sport-specific or ecologically-valid approaches (Moreau, et al. 2014). However, this approach is a topic of current scientific debate, as the varying levels of evidence for both validating or invalidating these forms of generalized cognitive training in relation to sports performance is emerging to support both perspectives in various ways based upon the limited scientific evidence that is currently available (Abernathy, et al. 2012, Walton, et al. 2018, Renshaw, et al. 2019).

Higher levels of certain cognitive abilities have been found to be characteristic of elite and high-performing athletes (Walton, et al. 2018). These cognitive skills may include perceptual-cognitive ability (the ability to identify and process contextual information & integrate it with pre-existing knowledge and motor abilities), reaction time, decision-making, working memory, attentional control, anticipatory skills, knowledge of sports-specific patterns, task-specific visual behaviors, and executive functions (Furley, et al. 2016, Mann, et al. 2017, Sakamoto, et al. 2018, Walton, et al. 2018). However, higher performance on certain cognitive tasks may depend upon the sport, recognizing that different sports have differential perceptual, cognitive and visual demands.

Different cognitive skills may be associated with different sports. For example, self-paced athletes may possess superior inhibitory skills, while externally-paced athletes may have superior problem-solving skills (Jacobson, et al. 2014).. Athletes of strategic sports have demonstrated superior abilities on task-switching and inhibition (sub-domains of executive functions), while athletes in static sports conditions have demonstrated worse performance on executive functioning tasks (Krenn, et al. 2018). This research demonstrates that not all training approaches may apply to all sports, and keeping sport-specificity in mind while designing such approaches is warranted. However, multiple scenarios in certain studies demonstrate that athletes out-perform non-athletes on these cognitive tests (Jacobson, et al. 2014).

While perceptual (or visual) skills are thought to be immensely important in sport, assessing the relative cognitive skills of athletes is considered to be essential to understanding performance (Garland, et al. 1990). While many approaches isolate training specific systems, such as targeting the visual system or cognitive systems, perception, action and cognition in sport are strongly intertwined. For example, in complex problem-solving situations in sports, higher level athletes seem to demonstrate superior visual strategies (Ripoll, et al. 1995). Such evidence supports assumptions that vision (perception), decision (cognition), and action (response) are intertwined, and modalities that seek to improve sports performance should consider these relationships. As such, a schema has been developed by Basevitch et al. (2020) to posit that more sport-specific training approaches that possess "higher-order" cognitive demands are more "functional", as sport may require integrated, variable and complex cognitive demands, as opposed to simplified forms of isolated training (i.e. reaction training with abstract cues in a non-sport-specific environment executed with sport-irrelevant movements).

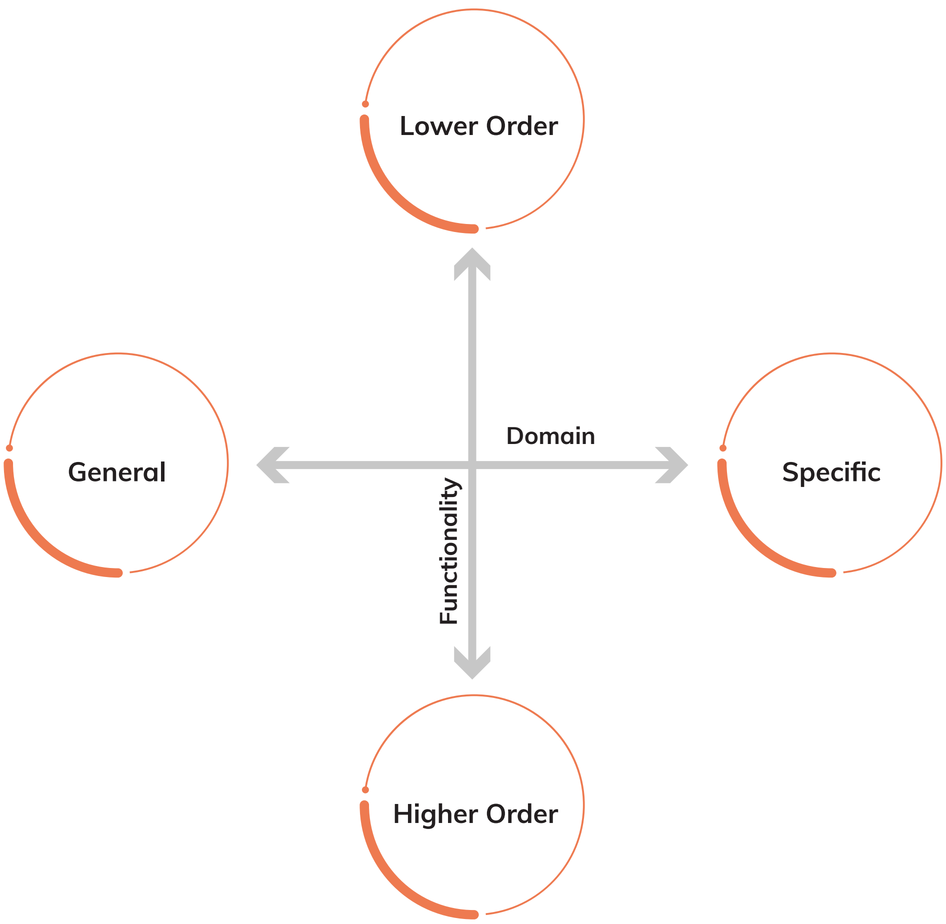


Figure 3: Basevitch, I., Boiangin, N., & Sáenz-Moncaleano, C. (2020). MOBILE TECHNOLOGIES AND PERCEPTUAL-COGNITIVE TRAINING. Advancements in Mental Skills Training.

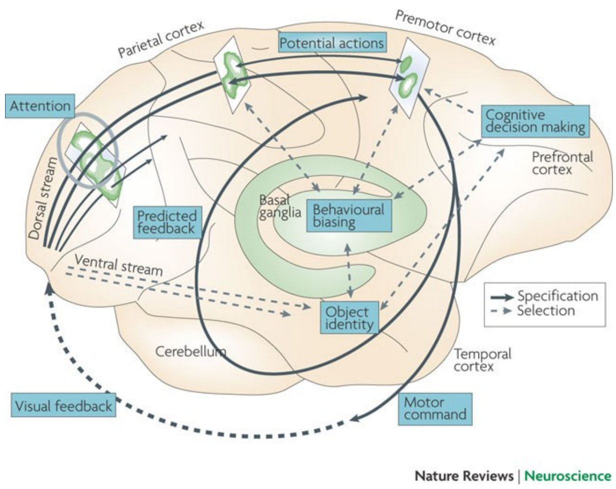
The Neurophysiology of Expert Athletes

In addition to behavioral and perceptual outcomes, such as cognition and perception, there is an interest in the neurophysiological characteristics that may underlie these observations. In a study using fMRI, expert athletes demonstrated greater activation in brain areas in the prefrontal cortex involved in the observation and understanding of others' action, or anticipation, when compared to novices (Wright, et al. 2010). As the result of expert athletes being able to better predict the potential outcomes of their opponents, experts have demonstrated increased improved speed and accuracy of their decisions (Yarrow, K., Brown, P., & Krakauer, J. W. (2009). Inside the brain of an elite athlete: the neural processes that support high achievement in sports. Nature Reviews Neuroscience, 10(8), 585-596.). These findings insinuate that it is not simply reflexive behaviors that allow athletes to exhibit speed and accuracy, but there is a large contribution of anticipation to these increases in performance.

Athletes exhibit precise motoric actions that are related to the goal in question, alongside enhanced related motor, perceptual, and decision-making abilities that are the result of extended periods of practice. In expert athletes, this performance is more automatic, insinuating that there is less relative cognitive demand and more efficient use of neural resources related to the motoric and cognitive processes in question (Yarrow, K., Brown, P., & Krakauer, J. W. (2009). Inside the brain of an elite athlete: the neural processes that support high achievement in sports. Nature Reviews Neuroscience, 10(8), 585-596.).

Structural imaging, with neuroimaging techniques such as MRI, have revealed that there are positive structural changes in the motor and sensory cortices of the brain.

Using functional neuroimaging, the observed neural resources in the brains of athletes are more efficient, requiring less neural resources to accomplish a task in comparison to novices, in which the use of more neural resources would be considered inefficient (Yarrow, K., Brown, P., & Krakauer, J. W. (2009). Inside the brain of an elite athlete: the neural processes that support high achievement in sports. Nature Reviews Neuroscience, 10(8), 585-596.). Changes in the functional status of the sensorimotor regions of the cortex might explain the ability for athletes to make decisions under the pressures of time. In general, athletes that take part in open-skill sports seem to have greater attentional function when compared to non-athletes, with top-down decision-making required in strategic sports being associated with the right side of the frontoparietal network. In addition, athletes who participate in more strategic sports are more accurate among decision-making tasks, while athletes in interceptive sports are faster among such tasks.



(Yarrow, K., Brown, P., & Krakauer, J. W. (2009). Inside the brain of an elite athlete: the neural processes that support high achievement in sports. Nature Reviews Neuroscience, 10(8), 585-596.).

Types of Transfer

In understanding the neurological characteristics and cognitive traits that elite athletes possess, it is of potential value to attempt to measure and train these cognitive skills. In an attempt to do so, there are various approaches that can be taken to train cognitive skills with the intent to improve sports performance.

In addition, it is important to understand how such training can transfer to environments on and off the field. In addition to understanding types of transfer, the “nature vs. nurture” argument is prevalent, as athletes may perform well in laboratory and sport-specific settings, but the desire to “reverse engineer” and train certain traits may only translate to improving specific skills, rather than sports performance (Voss, et al. 2010).

There are different types of “transfer”, which are important to understand when evaluating various training methods. These theories of transfer are important to consider, especially in interventions that seek to be “additive” to athletes as seen in brain training products (Renshaw, et al. 2019).

One type of transfer is “near transfer”, whereby practicing a task only improves performance on measures directly related to that task. For example, training reaction time on a computer that then improves performance on a computerized assessment of reaction time would be considered near-transfer. Task-specific transfer is similar to near transfer, but is more “near” than near transfer itself, as task-specific transfer alludes to improvements in the training task in question (Fleddermann, et al. 2019).

An example of task-specific transfer is improving in the same task that is given, drawing similarities to near-transfer. In addition, while the majority of evidence of perceptual and/or cognitive training demonstrates near-transfer via the enhancement of certain cognitive processes, enhancement or improvements in task-specific performance should not be confused with far-transfer (Moreau, et al. 2014).

“Far transfer” occurs when training improves unrelated measures of performance, typically in real-world or sport-specific settings, and is the most sought-after. Far-transfer would occur when a type of training improves measures of sport performance that are unrelated to training tasks. In order to demonstrate near or far transfer, different assessments can be selected.

Often, neuropsychological and cognitive assessments are used to assess cognition, and while these are interesting and relevant, they may have limited use for athletes and coaches directly. Other assessments might include sports-specific decision-making scenarios, questionnaires, and neuroimaging (Walton, et al. 2018). Far transfer is often confused for “further transfer”, which refers to training improving performance on sensorimotor sports skills, which is to say that performance transfers to an on-field competitive game (far transfer) (Hadlow, et al. 2018). Given that athletes and sports environments have an incredible amount of variables, this proves challenging to assess.

Training Approaches

The "process training" approach isolates differentiated functions associated with athletic performance, and addresses them through targeted training. For example, computerized cognitive training primarily targets the training of cognition, but not motor behavior. Similarly, sports vision training primarily targets the visual system, whereas agility training primarily targets gross-motor responses to a stimulus. Cognitive training, vision training, and agility training are all examples of "process training", by which a part of the body is targeted in isolation (eyes, brain, body), rather than trained simultaneously. In addition to this modular approach, "sub-modules" of the brain are attempted to be targeted and trained. These isolated process-training approaches may provide "general transfer" (synonymous with near-transfer), but methods to improve "specificity of transfer" (or far-transfer to sport specific outcomes) are needed. Computerized cognitive training has primarily demonstrated near-transfer, and for the purpose of sport, should seek to target far-transfer (transference to untrained and sports-specific tasks) by possessing certain training characteristics that make it more relevant to sport. Perceptual-cognitive training approaches should also consider how to train athletes to differentiate relevant versus irrelevant (or distractor) stimuli in the context of sport, and how they couple this information with motoric action (Renshaw, et al. 2019).

As an alternative to process training, the approach of "ecological dynamics" places an emphasis on the individual (which is an integrated system) and the relationship to the environment. Since the brain is posited to be understood as a complex-adaptive system, the environment is also thought to be unpredictable with sport-specific constraints (Renshaw, et al. 2019). In comparison to the process training approach, the ecological approach understands the athlete in a more complex framework. Instead of targeting one function of an athlete (i.e. cognition or vision), the perceptual, cognitive and motor systems an athlete possesses are integrated, working to interact within a sport-specific environment. Given the nature of the ecological approach, process training approaches that seek to enhance performance in a singular system (i.e. cognition) with the goal of improving performance may be limited given the complex interactions that these systems involve. In addition, applying the adaptations to a sport-specific environment is an additional challenge, as certain abstract stimuli (i.e. lights) may not always transfer to sport-specific scenarios, where such abstract stimuli may not be encountered. In addition, the knowledge and intention within a sports environment are not always reflected in more modular approaches. As such, perceptual, cognitive, and motor systems should be trained in an integrated and coupled manner within sport-specific contexts if chances for far-transfer were to theoretically improve. Lastly, whereas the process approach insinuates that single training modalities can apply to all athletes, the ecological dynamics approach considers the individual athlete, recognizing a high degree of variability among perceptual, cognitive and motor behavior (Renshaw, et al. 2019).

Training Methods

In the interest of improving sports performance, various methodologies, technologies, and approaches have been developed, with more solutions being developed in the coming future. There are various forms of training perceptual, cognitive, and/or motor skills in athletes that have been employed in both research and sports-training settings. There are various examples, names, and terminology underlying many of these training approaches, and there are rarely agreed-upon standards that transcend both research, commercial and sport-settings. These approaches to training include the following, all of which with varying degrees of research, efficacy, and specificity (Fadde, et al. 2018); Computerized Cognitive Training (Walton, et al.

2018, Moreau, et al. 2014), Sports Vision Training (including Stroboscopic and Visual Occlusion Training) (Van der Kamp, et al. 2007, Applebaum, et al. 2018), Virtual Reality Training (Stone, et al. 2018), and Reaction Training Lights, LEDs, & Screens (Renshaw, et al. 2019).

Currently, there is no agreed upon terminology that describes the modality or process of training that provides a stimulus and, sequentially or simultaneously, a motor response. Some terminology that has utilized in literature includes; Perceptual-Cognitive training (such as 3-dimensional multiple object tracking) (Renshaw, et al. 2019), Reaction time training, Modified Perceptual Training (Hadlow, et al. 2018), Stimulus-Response Compatibility Training (Hirao, et al. 2018), Reactive Agility Training (Pojskic, et al. 2018), Attentional Shift Training (Ziegler, 1994), and Cognitive-Motor Dual-Tasking (Schaefer, et al. 2020, Moreira, et al. 2021).

Similar to perceptual and/or cognitive training approaches in athletes, these methods generally lack sufficient standardization, research and agreed-upon terminology. In addition, many of these methodologies are criticized for their partial incoherence with the ecological approach. The “motor component” of many of these approaches are either a button-press or a repetitive gross motor response, or the cognitive component of training is unspecified, mimics generalized cognitive training, or is typically non-specific to sport (Renshaw, et al. 2019), although the validity of these approaches are still being researched and debated.

Sports-Specificity

Perceptual-cognitive skills, including pattern matching, decision-making, and anticipation skills, are considered to be important across multiple sports (Belling, et al. 2015). Based on the various research and commentary cited on what effective brain-based sports training approaches may include, there are several characteristics in sports training interventions that should be present if improvement in perceptual-cognitive skills were to have the greatest chance of far-transfer to sport (Broadbent, et al. 2015).

These characteristics, which would appeal to the ecological dynamics approach, would include; combined targeted systems of the body (visual, cognitive, motor, etc), sport specificity (including training environment, equipment and sport skill), specificity of sport action in anticipatory performance (Mann, et al. 2010), Reactive, Unpredictable, Random Stimulus (ideally in response to another athlete), Contextual Interference, and Gross-Motor Responses (ideally sport-specific movements). Modified perceptual training (MPT) has been offered as a classification referring to any on or off-field methods of training attempting to train and improve one or more specific perceptual processes in athletes (Hadlow, et al. 2018).

Research presents upon the potential importance of sport-specific contextual interference, whereby unpredictable stimulus associated with the constraints found in sport may increase the likelihood of far-transfer to sport when compared to predictable perceptual-cognitive training without any sport-specific constraints present.

In relevance to sport-specific context, the term “task representativeness” has been utilized to convey to what degrees training tasks represent the complexity and specificity of tasks or scenarios that would be found in sport (Klostermann, et al. 2019). For example, a study of motor performance and gaze behavior in 13 youth basketball players revealed that both motor and visual performance improved more when shots were contested by defenders rather than uncontested (Van Maarseveen, et al. 2018).

The concept of “task representativeness” is present within the models of “representative learning design” (RLD), which seeks to provide a framework for designing effective tasks in sports practice that may better transfer to competition. RLD suggests that the factors needed for this include perceptual-cognitive processes linking information to action (Hadlow, et al. 2018). This is potentially more simply understood as a “perceptual-cognitive-motor” loop, or “PCM’’.

The Performance Loop

Figure 4: Credit to SwitchedOn

To further elaborate on elements that, if present, are more likely to contribute to far-transfer in sport as it relates to improvements in sports performance, it is helpful to reivist the framework of modified perceptual training (MPT) from Hadlow and colleagues (2018). The MPT framework compares various perceptual and/or cognitive training products in various ways, with three particular categories of criteria being outlined. The first category is targeted perceptual functions, or the cognitive, visual and/or motor skill being trained that is considered relevant to the athlete and sport in question, keeping the skill level of the athlete in mind. The second category is the presented stimulus, and how it corresponds to sport-specific contexts.

For example, do opponents or objects (virtually or otherwise) behave in a way that is authentic to the sport, or is abstract or general stimuli presented that is not found in sport? Thirdly, is the response relevant to a sports context, such as responding with a sport-specific action, or does it involve clicking a button or moving a wand? Finally, the MPT framework assumes that if these three categories are represented in a sport-specific manner, and if tools target higher-order perceptual-cognitive functions, and involve sport-specific actions, that the likelihood of enhancing targeted perceptual-cognitive abilities and/or far-transfer to sport is more likely (Fadde, et al. 2018, Hadlow, et al. 2018).

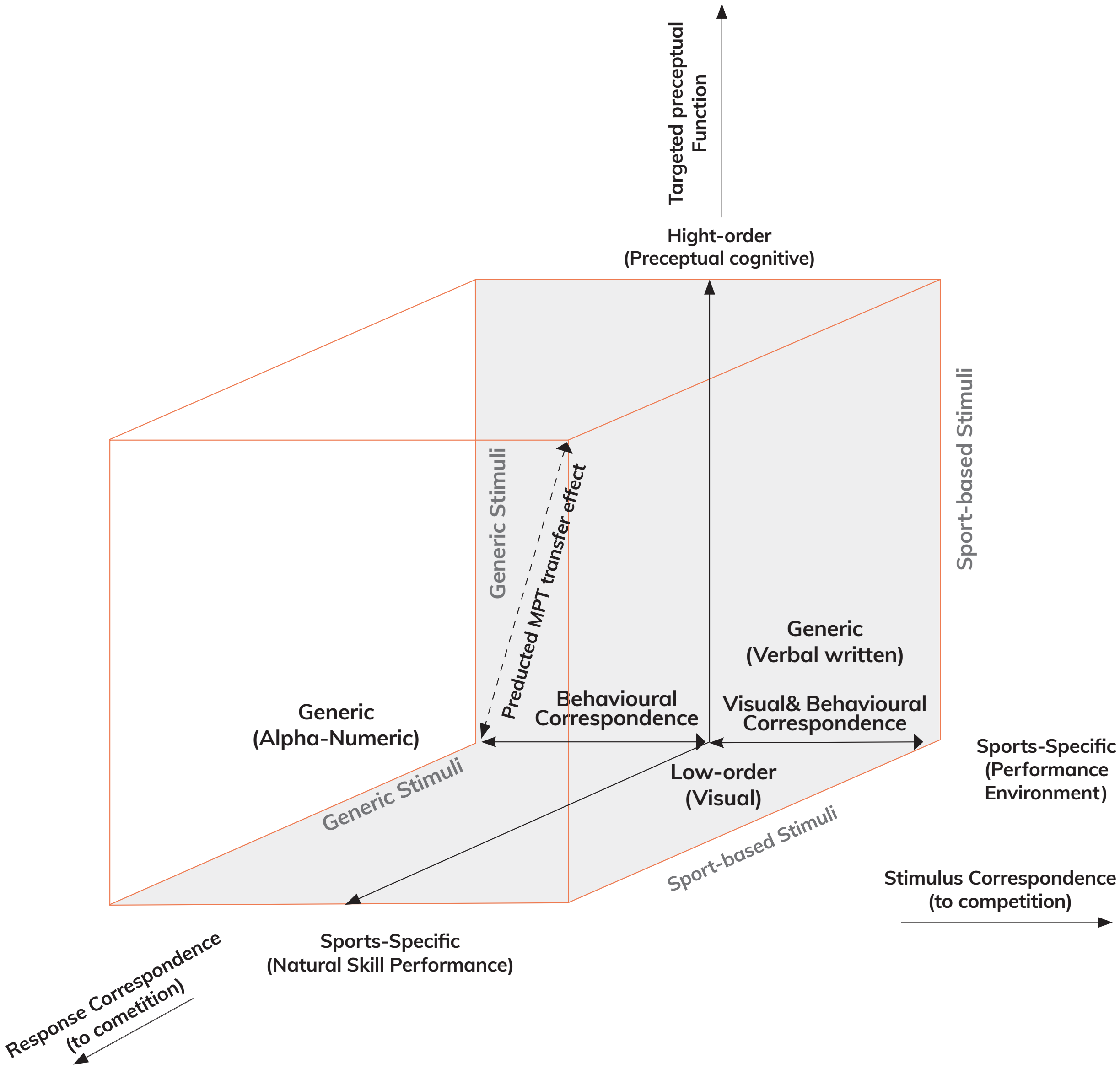


Figure 5: Hadlow, S. M., Panchuk, D., Mann, D. L., Portus, M. R., & Abernethy, B. (2018). Modified perceptual training in sport: a new classification framework. Journal of Science and Medicine in Sport, 21(9), 950-958.

There are several other characteristics that perceptual-cognitive training methods may seek to possess if they were to provide value in sport. Considering that skill-level is an important consideration in perceptual-cognitive training of athletes, and understanding that improvements in task-specific performance are imminent, including adaptive difficulty and principles of "progressive overload" may be important elements to include in perceptual-cognitive training modalities.

Evidence for the importance of adaptive difficulty has demonstrated superior outcomes in virtual reality training (Gray, 2017) and in perceptual-cognitive training approaches, such as 3D multiple object tracking (Faubet, et al. 2012, Harris, et al. 2020), and in more traditional working memory training tasks (such as the n-back task) (Vartanian, et al. 2021) when compared to groups that did not participate in adaptive training conditions.

Dual-Processing of Information

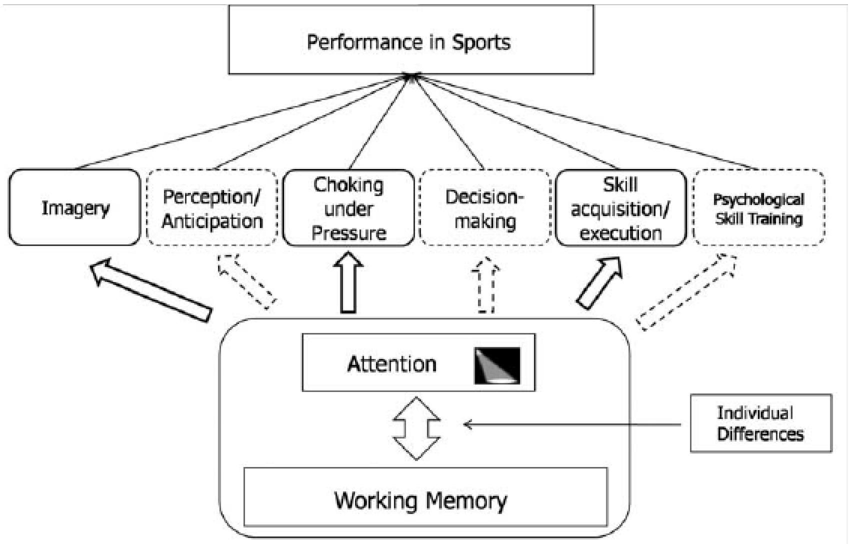
Working memory is a component of executive functioning that involves the temporary storage and manipulation of information, and plays a role in the allocation of attention and the filtering of irrelevant stimulus, in addition to playing a key role in other executive functions such as inhibition and cognitive flexibility. Visual attention is also an important perceptual-cognitive skill, although the evidence linking both visual attention and working memory with sports expertise is limited (Buszard, et al. 2017, Memmert, et al. 2009). However, some studies have found that there is a relationship between the control and span (or capacity) of working memory in expert athletes (Vaughn, et al. 2020).

Laboratory experiments link the acquisition of rather simple motor tasks with working memory tasks, this may not have as much relevance to complex motor tasks found in sport (Buszard, et al. 2017), although some research in VR-based anticipatory training has found that training of more simple tasks may lead to improvements in anticipation within more complex tasks, and task training with greater complexity and variability might be more efficacious (Gray, 2009). While investing in computerized working memory training is not recommended due to a lack of available convincing evidence, it is instead recommended that athletes and coaches invest in sport-specific training (Furley, et al. 2016) where working memory and visual attention demands may be emphasized in a context-specific manner.

More recent models of working memory reveal a concept known as "dual-processing theory", which posits that attentional control can vary depending on the athlete's allocation of focus.

It has been posited that automaticity of motor tasks (such as dribbling a basketball) relieve the athlete of internal focus, so that they may instead focus on information related to goal-directed behavior (avoiding opponents or making a shot), whereas the opposite would cause decreases in multiple aspects of sports performance The behavior associated with dual-processing can be understood as dual-tasking, whereby two concurrent tasks with separate, measurable goals are conducted simultaneously.

Decerements in motor and/or cognitive performance under dual-task conditions are called dual-task interference, with the measurable decreases in performance being called dual-task costs. Research has found that experts perform better under dual-task conditions when compared to novices or non-athletes (Gray, 2004, Morieira, et al. 2021, Schaefer, et al. 2020). The potential role of dual-tasking to improve motor and/or cognitive performance will be explored in a later section.



(Furley, P. A., & Memmert, D. (2010). The role of working memory in sport. International Review of Sport and Exercise Psychology, 3(2), 171-194).

The Challenge Point Framework, Motivation & Fatigue

Motivation also likely plays a key role in the changes in performance that an athlete may experience as the result of any intervention seeking to improve one or more elements of performance. Regardless of how ecologically valid a task may be, self-directed motivation may create "psychological placebos" and either directly or indirectly affect levels of confidence in certain ecologically valid scenarios. In addition, voluntary exercise has been shown to modify synaptic plasticity in rats when compared with involuntary exercise (Farmer, et al. 2004).

However, this is difficult to translate to human models, let alone athletes, although it is generally agreeable that self-motivated learners will likely improve task-relevant outcomes. Motivation has also been found to improve levels of enjoyment and engagement in cognitive training interventions, although more research is needed to determine if this improves cognitive outcomes in comparison to more bland interventions, which are all too common in laboratory experiments (Mohammed, et al. 2017).

Another element of sports training and performance is mental and/or physical fatigue. Many sports, whether open or closed activities, often require the allocation of attention for an extended period of time and concurrent physical exertions, with various in duration, frequency and intensity. In studying the effects of fatigue on athletes, experiments have utilized computerized cognitive tasks (such as the Stroop task), mental imagery, psychological techniques, and/or physical exhaustion to measure the effects of fatigue on cognitive and/or physical performance (Coutts, et al. 2016, Marcora, et al. 2009). Both high physical and mental demands have been found to induce cognitive and neurophysiological fatigue and reduce physical and cognitive performance (Blain, et al. 2019, Chatain, et al. 2019, Pageaux, et al. 2018, Van Cutsem, et al. 2017).

This research has given rise to methods of training that seek to fatigue athletes in an effort to improve the capacity for fatigue or create "mental or cognitive endurance" or "cognitive overload" in an effort to improve performance by increasing fatigue tolerance, perception of fatigue, and "cognitive capacity." So far, these methods have not produced sufficient evidence in demonstrating transfer to sport (Renshaw, et al. 2019). As with perceptual-cognitive/motor training, these methods should also pertain to these principles of ecological dynamics. In order to laboratory experiments on mental and/or physical fatigue training to possess a greater likelihood of transfer to sport, such methods should be performed in contexts that are relevant to the sport in question, although more research is needed to better understand the complexities underlying fatigue in sports (Coutts, et al. 2016).

In relevance to motivation, fatigue, and motor learning, the Challenge Point Framework has been proposed as a framework to contextualize practice and training conditions, especially in relevance to sport and skill development. The Challenge Point Framework states that different levels of performance require increases in task demands that parallel the improvements in skill that can occur with practice, ideally leading to an "optimal challenge point" in which task demands are not too demanding or frustration beyond the athlete's current skill level, and are not below the skill level of athlete leading to boredom. A matching of the task difficulty to an athlete's skill level, based on information processing theories, and consideration of the task environment would likely optimize the outcomes of certain practice conditions within motor learning (Guadagnoli, et al. 2014).

The challenge point framework also posits that higher levels of contextual interference (or randomly changing task or practice conditions, also associated with random practice) are more likely to decrease task performance (as contextual interference increased task difficulty) but are more likely to transfer to the real-world demands of sport, although more research is needed to determine the optimal conditions and practice frameworks are most appropriate, when to utilize such conditions, and what conditions would likely best transfer to sport (Brady, 2008). In other words, lower levels of contextual interference may be more appropriate for novices (task simplicity and lower task demands), whereas higher levels of contextual interference may be more appropriate for higher-skilled athletes (greater task complexity and increased task demands). In addition, random practice may be better suited for lower task demands, whereas blocked practice may be appropriate for higher task demands (Guadagnoli, et al. 2014), although the combination of contextual interference, high task demands, and randomization may be valuable in the context of training perceptual-cognitive skills in athletes given the appropriate and relevant development of tasks and their constraints.

Another way to contextualize the Challenge Point Framework in relevance to perceptual-cognitive training is by acknowledging the difference between "hot" and "cool" executive functions, as defined in earlier sections. Most training off-field is conducted at a pace that may be below the athlete's skill level in a "cool" manner, which likely possesses less temporal demands and may be conducted in a closed-skill environment (i.e. pre-planned, low complexity, self-paced agility training).
In comparison, a more ideal training environment for athletes with higher levels of skill would likely consist of more open-skill training conditions, emphasizing "hot" executive functioning (i.e. inhibitory control, cognitive flexibility, and working memory demands), with greater temporal demands and greater task complexity. The latter training environment would be more likely to mimic the demands of sport and adhere to the optimal challenge point framework, recognizing the potential value of higher levels of contextual interference as long as the task conditions selected were matched to athlete's current level of skill, and progressed overtime, borrowing from the principles of progressive overload and overspeed training, (Stone, et al. 2002, Faubet, et al. 2012) to match an athlete's increasing level of skill (Broadbent, et al. 2015).

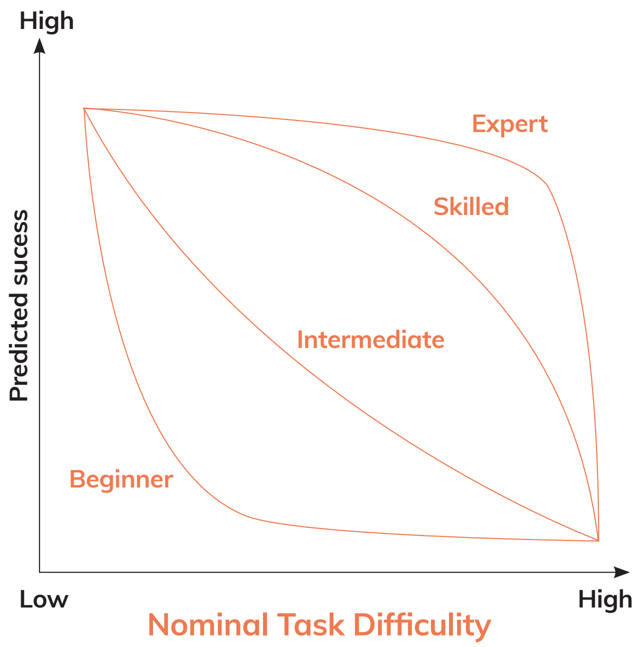


Figure 7: Guadagnoli, M. A., & Lee, T. D. (2004). Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. Journal of motor behavior, 36(2), 212-224.

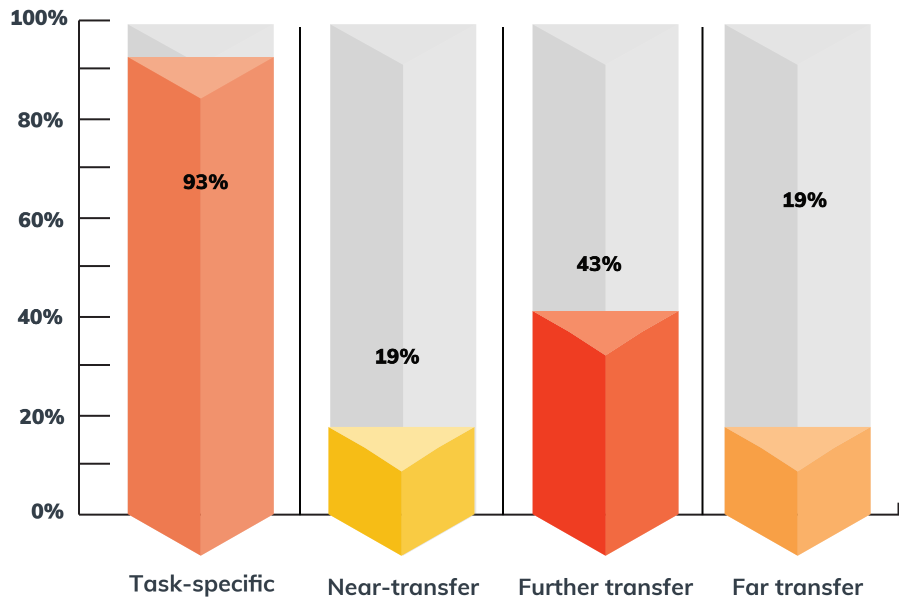
Perceptual-Cognitive Training in Sport

In a systematic review of the transfer effects of perceptual-cognitive training in sports (Zentgraft, et al. 2017), 16 studies were reviewed. Of these studies, it was found that 93% of them addressed task-specific practice effects (i.e. athletes improved at the task being trained), 19% addressed near-transfer effects (i.e. improvements in tests of a similar domain to the trained task), 42% addressed further transfer (i.e. transfer to isolated sensorimotor sports skills) and only 19% of the studies addressed far transfer (i.e. transfer to game-like performance in competition). Generalized computerized perceptual and/or cognitive training primarily lacks sufficient demonstration of far-transfer into dissimilar, non-digital and more ecological tasks, and only near-transfer to similar tasks (Renshaw, et al. 2019). Given that, in elite sports, far transfer from a training approach to sport-specific settings on the field in a dynamic, goal-oriented setting is most desirable, the amount of current evidence demonstrating far transfer of these process-oriented computerized perceptual and/or cognitive training methods, including many analog training approaches utilized in sports vision training, is not convincing (Fleddermann, et al. 2019, Formenti, et al. 2019, Kolstermann, et al. 2019, Renshaw, et al. 2019, Scharfen, et al. 2020).

In the quest for interventions that may better translate to sport (i.e. far-transfer), it may be helpful to assess research that incorporates certain elements that are more proximal to ecological validity and sports-specificity, while still possessing certain elements of the process-training approach.

As defined earlier, modified perceptual training (MPT) is a framework that possesses the capacity to place several training modalities on a various spectrums, differentiating general from sport specific stimuli, general vs. sport-specific environments, and near versus far transfer as a result of these forms of training (Hadlow, et al. 2018).

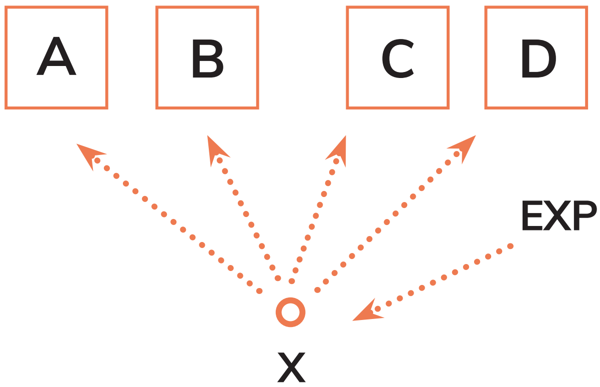
While the majority of current solutions in the commercial market do not possess sufficient demonstration of far-transfer, nor do they possess enough sport-specific relevance, it is challenging for products to translate from the laboratory with methodologies such as sports-specific perceptual-cognitive training that demonstrate more promise for far-transfer. In addition, athletes may not possess certain financial and technological affordances to access such technologies, and therefore inexpensive and scalable solutions that possess several characteristics pertaining to ecological validity.



Anticipation in sports is an important aspect of the perceptual-cognitive-motor relationship, perhaps one of the most important in the perception and cognition aspect of athletic performance. Anticipation is explored in a multitude of ways, and the exploration of different methods for training anticipation is important for understanding potential best practices. In an attempt to study this, Abernethy and colleagues (Abernethy, et al. 2012) conducted a study in 60 handball players to compare the efficacy of different methods for improving sport-specific anticipation, specifically the prediction of the direction of a shot based on the position of another player's shoulder within a video.

Athletes were assigned to one of four conditions; an "explicit learning" group that were given rules (i.e. certain shoulder positions equal certain shots), a verbal cueing group (i.e. no rules given), a color cueing group (with a colored red dot over the shoulder, showing just the arm), and an implicit learning group (are sequential videos that same or different). The explicit learning group demonstrated the greatest improvements in anticipation, while the color cueing group experienced worsened anticipation skills. However, the authors of this study clarify that color cueing in a different context may find different, more advantageous results, especially if the cueing is coupled with relevant actions, and if motor responses coupled with relevant cues are more ecologically valid, rather than more superficial attempts to mimic sport (Abernethy, et al. 2012). For example, some researchers have proposed that by adding motor responses to video-based occlusion tasks, there may be a potential increase in transfer to sport (Fadde, et al. 2018).

In addition, sport-specificity of a given stimulus seems to be important. Early research has been conducted on comparing the effectiveness of a reactive stimulus during agility training, with response to opponents being more effective than reacting to lights or arrows, which are not considered to be sport-specific (Young, et al. 2013). However, these findings were constrained to only reactive agility training (RAT) assessment, not training, and the population was only in Australian Football (Young, et al. 2011). Another study utilizing perceptual-cognitive training (through video training) in softball players has posited that non-sport-specific stimuli such as arrows may not significantly cause far-transfer (Gabbett, et al. 2007), yet the study of coupling such stimuli with sports-specific movements, equipment, environments, and relevant movements has yet to be studied.



Ziegler, S. G. (1994). The effects of attentional shift training on the execution of soccer skills: A preliminary investigation. Journal of Applied Behavior Analysis, 27(3), 545-552.

It is possible that reaction to lights or arrows in the context of a more sports-specific situation with more relevant information-action coupling may still be valuable, especially when sports-specific training on or off-field is not always available, or when specific training regimens become repetitive and predictable, and more unpredictable stimuli could be generated by certain technologies when no coach or training partner is available.

In addition to perceptual-cognitive abilities, athletes often need to shift their attention to different cues (shifting attention), as well as inhibit irrelevant information (selective attention), in order to perform successfully in sports, especially those that are open-skill sports (Monsma, et al. 2017). In order to train this, Susan G. Ziegler formulated and studied a method called "attentional shift training" in 1994, whereby different cards consisting of letters, shapes, numbers and colors correspond to a type and direction of a pass within soccer players. The cues were visually displayed in front of a soccer player controlling a ball, and a coach would verbally call out which target to focus on, in which the athletes would then visually scan, identify, and pass the ball to the correct target.

While the athletes did improve their performance on a sport-specific test (scoring more goal points in a simulated sport scenario) the sample size was very small (4 players) and the methodology lacked rigorous design, in addition to the study's lack of recency, statistical power, or replication (Ziegler, 1994). However, it is interesting that this approach to training preceded the origination of computerized perceptual and/or cognitive training methods that are now being criticized. In addition, certain methods mimicking this "attentional shift training" have been observed in elite sports training in a variety of ways, with high-level coaches vouching anecdotally for their value.

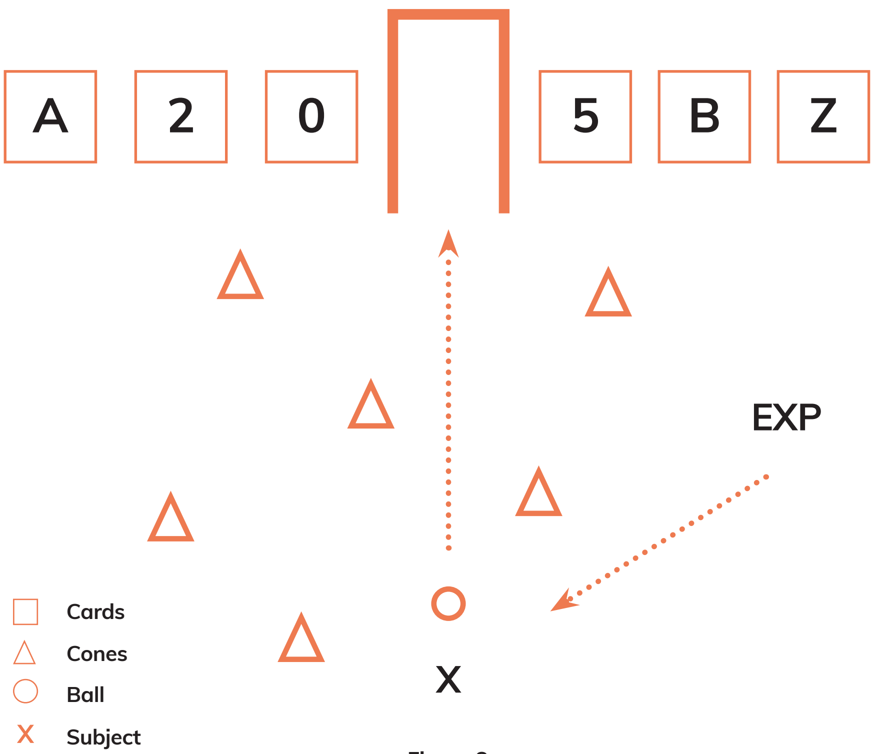


Figure 8

Integrating Cognitive & Motor Tasks

While many experiments and approaches take an "isolated" approach to training (i.e. training cognition via computerized tasks, or training motor skills through repetitive physical practice), there is value to combining cognitive and motor tasks. This approach is not entirely novel, yet often misunderstood, as there are various ways to approach the combination of cognitive and motor tasks. Authors Herold, et al. (2018) describe sequential motor-cognitive training (whereby a motor and a cognitive task or conducted at separate times) and simultaneous motor-cognitive training (whereby motor and cognitive tasks are performed at the same time), also known as dual-tasking. The selection of the cognitive task and how it is performed in relevance to the motor task is of important consideration, what could be understood as "task relevance." One approach is to engage in a motor task (typically a closed skill task, such as cycling, walking, or jogging) and "add" a cognitive task as an irrelevant "distractor" from the motor task (such as counting backwards or reciting every other letter of the alphabet). A different and perhaps more efficacious approach would be to "integrate" a cognitive with a motor task, whereby the goal of the cognitive task and the motor task are shared, such as seen in real-life (participating in dance or sport, recalling items walking through a store, etc). Both approaches have demonstrated various levels of improvement in both cognitive and/or motor outcomes (primarily in children or older adults), although the "simultaneous and integrated motor-cognitive" approach may possess greater ecological validity and more significantly improve motor and/or cognitive outcomes (Herold, et al. 2018). Therefore, dual-task training that incorporates relevant tasks that are "integrated" with also relevant motor tasks are of potentially greater value across multiple populations.

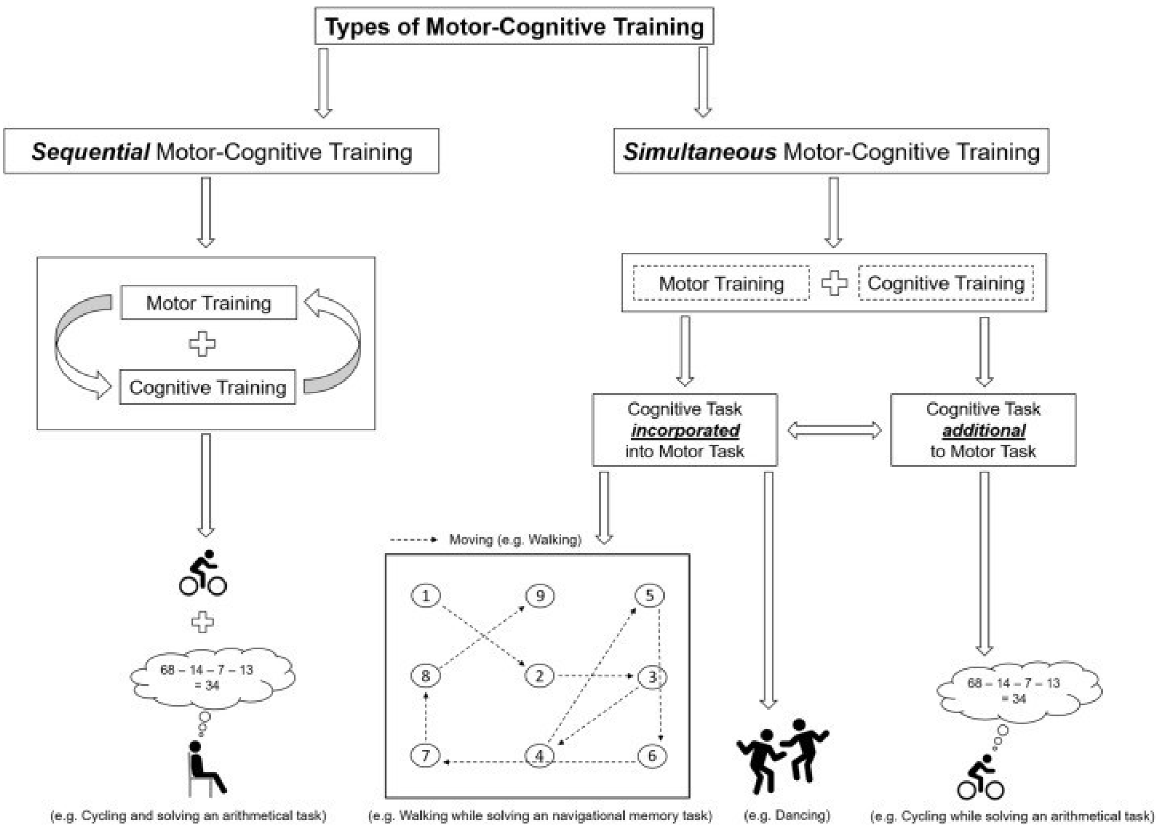


Figure 9: Herold, F., Hamacher, D., Schega, L., & Müller, N. G. (2018). Thinking while moving or moving while thinking–concepts of motor-cognitive training for cognitive performance enhancement. Frontiers in aging neuroscience, 10, 228.

Dual-tasking (or dual-task training), as previously described, is a method of training gaining recognition and popularity both in research, clinical, and performance settings. There is a larger body of literature suggesting that dual-task training (including moving with both relevant and irrelevant cognitive tasks) can improve cognitive and motor outcomes, often more significantly than single or separate modalities of training (Herold, et al. 2018, Laurenroth, et al. 2016). This includes exergaming, which are video games that require physical movement in order to participate in the game. These exergames can either be general or specific in the cognitive or motor tasks they are targeting, and have found to significantly improve cognition in older adults (Stojan, et al. 2019) and children (Best, 2015), including both clinical and non-clinical populations (Fang, et al. 2019, Stanmore, et al. 2017). However, many of these exergames would be considered “out-of-date” in terms of technological adoption and usage (such as the Nintendo Wii, Xbox Kinect, or Dance Dance Revolution), and may not have relevance or utility for athletic performance, as they have been used as an “active control group” in studies observing the effects of perceptual-cognitive training in athletes. However, developments in technology and influences from cognitive training has already begun to usher in “game-like” and immersive version of perceptual-cognitive/motor training in athletes, and exergaming has been proposed as potentially valuable for the physical and cognitive training of eSports athletes (Martin-Nieckeden, et al. 2020).

Although the evidence for dual-tasking improving motor and cognitive outcomes in older adults, children, and clinical populations is encouraging, these results cannot be immediately assumed or translated to athletes and outcomes associated with sports-performance. As athletes, especially those at a higher-level, are already “experts in the laboratory” as high performers on perceptual-cognitive tasks in comparison to novices or non-athletes (Voss, et al. 2010), there is likely a “ceiling effect” for cognition in athletes, especially those who are at an age where certain cognitive functions have peaked in development, depending on the skill level of the athlete, and/or depending upon the task-specific improvements in performance (Moreau, et al. 2013, Walton, et al. 2018).

In a recent systematic review of 18 studies on the acute (which primarily used dual-tasking as a “distractor”, finding that higher-level athletes and those undergoing dual-task training had reduced dual-task costs) and chronic effects of dual-task training in athletes, it was found that 5 of the studies associated with the long-term (chronic) effects of dual-task training led to improvements in working memory and attentional control in athletes (Morieria, et al. 2021), although more demonstration of far-transfer to sport and replication of these studies are warranted. However, there is more evidence establishing the value of dual-task assessment, including simple measures such as reaction time (Lempke, et al. 2020), and training in athletes who have sustained concussions (Kleiner, et al. 2018), athletes with intellectual impairments (Van Biesen, et al. 2018) or undergoing ACL rehabilitation (Ness, et al. 2020).

Dual-tasking assessments and interventions in these various applications has demonstrated potential validity in improving functional, performance, cognitive and/or motor outcomes. These examples represent promising potential for dual-tasking and perceptual-cognitive-motor training in athletes within clinical rehabilitation settings, although more research is needed to determine best practices and as to which methods would be most effective for the rehabilitation outcomes in question, and whether or not improvements in these outcomes translate to sport, or rather improve the efficiency of orthopedic or neurological rehabilitation. In addition, the potential value of cognitive-motor training approaches in the potential role of slowing cognitive decline or improving quality of life after sport or playing a role in childhood development warrants more research.

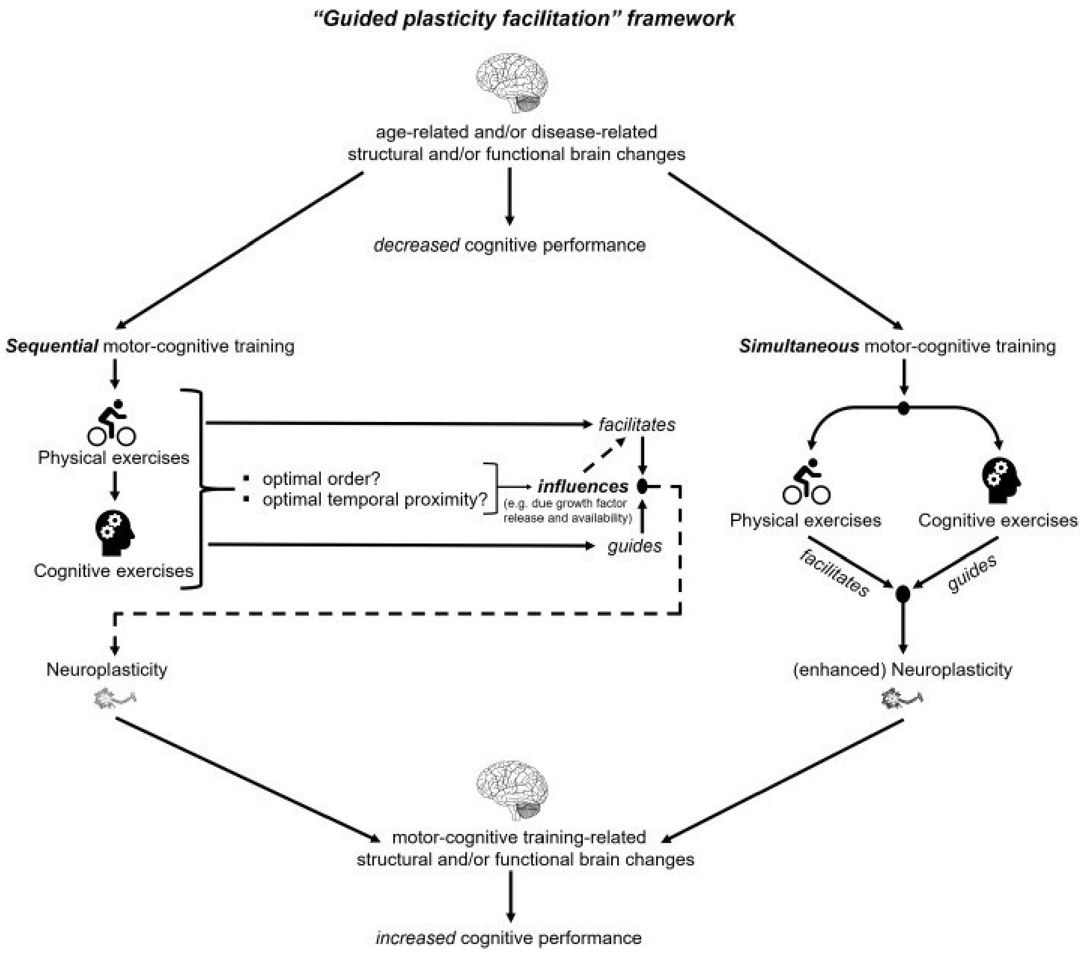


Figure 10: Herold, F., Hamacher, D., Schega, L., & Müller, N. G. (2018). Thinking while moving or moving while thinking–concepts of motor-cognitive training for cognitive performance enhancement. Frontiers in aging neuroscience, 10, 228.

Reactive Agility Training

Considering that the motor responses of perceptual and/or cognitive training are typically not sports specific (using buttons, wands, or general movements), it is of potential value to identify motor responses that can integrate with cognitive stimuli that may be more ecologically valid. In addition, sporting activities themselves inherently possess integrated dual-tasking. Agility training has recently been redefined as; "a rapid whole-body movement with change of velocity or direction in response to a stimulus", which may include visual and cognitive components (Sheppard, et al. 2006). Reactive Agility Training and Assessment are both emerging topics in sports science research, as it posited that such approaches more better mimic sport scenarios due to their open-skill (unpredictable nature), compared to more traditional tests of agility, which are often more closed-skill (predictable) (Sheppard, et al. 2006, Pojskic, et al. 2018). In addition, open-skill athletes tend to outperform closed-skill athletes on certain cognitive tests (Tsubouchi, et al. 2016). Reactive agility may also represent the intersection of ecologically-valid sports tasks and process-oriented and specific integrated dual-tasks, with technology potentially utilized in various ways. In addition, agility performance (often referred to as "motor fitness") and/or agility training has been correlated with improvements in certain aspects of cognition in comparison with other modalities of exercise within populations such as children (Moradi, et al. 2019), military (Lennemann, et al. 2013), older adults (Laurenroth, et al. 2016), sports-related concussion (Wilkerson, et al. 2020), ACL-rehabilitation (Kakavas, et al. 2020), long-term athletic development (Granacher, et al. 2017) and childhood development (Lloyd, et al. 2013), and in various sports, such as team-sports (Paul, et al. 2016).

Agility training is already widely-adopted and is considered rather universally adopted in sports across various groups (regardless of age or expertise), particularly open-skill sports, and is both affordable, scalable and accessible. Agility training itself is a key feature in strength and conditioning programs (Spiteri, et al. 2018) and could be considered an open-skill activity (Serpell, et al. 2011), even if agility techniques are repetitive or well-rehearsed. However, making agility more "reactive" could facilitate a more "open skill environment" in comparison to agility drills that are more predictable, pre-planned, do not possess dual-task conditions, and are outside sports-specific contexts (Scanlan, et al. 2015). Closed-skill techniques may be helpful for developing fundamental sports skills, however a more randomized, task-based, and reactive approach to agility training that incorporates visual and cognitive elements more likely reflect the true nature of sports (Jeffreys, 2011).

Reactive agility training has been shown to be effective in some sports performance outcomes (Scanlan, et al. 2014, Spiteri, et al. 2018) and in comparison to traditional agility training (Formenti, et al. 2019, Young, et al. 2015, Caserta, 2017 Fischer, et al. 2015), and certain forms of reactive agility assessments may provide significant value for screening athletic performance (Serpell, et al. 2011).

Although, one study found that there was no significant difference between open or closed skill warm-ups on acute agility performance (Gabbett, et al. 2008), which may yield considerations for when reactive agility training would be most effective, and in what dosage of training. More research is needed as these studies are limited in their methodological design, statistical power, and participant diversity (sport, gender, age, etc).

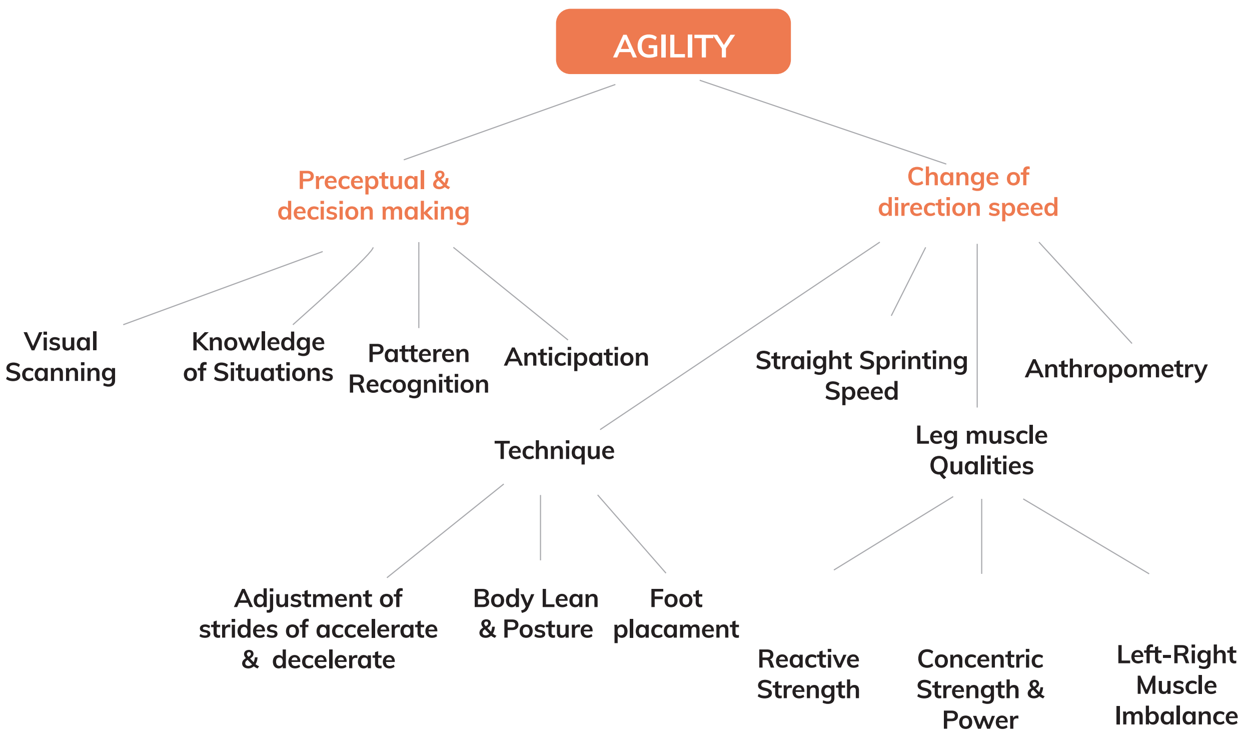


Figure 11: Serpell, B. G., Young, W. B., & Ford, M. (2011). Are the perceptual and decision-making components of agility trainable? A preliminary investigation. The Journal of Strength & Conditioning Research, 25(5), 1240-1248.

Reactive agility training is best conducted in sports-specific environments (Young, et al 2013), combined with both general and specific perceptual-cognitive demands (Jeffreys, 2011), incorporate both general and sport-specific equipment, and be performed with teammates and opponents. Reactive agility also consists of both perceptual-cognitive and decision-making components, both of which have been proposed to be trainable and important elements of agility performance, in which coaches have been encouraged to address in sports conditioning and training (Serpell, et al. 2011). In addition, change of direction (COD) training may provide superior outcomes in sport-specific agility tests when compared to linear agility or speed training (Chaalali, et al. 2016, Paul, et al. 2016), although more research is needed for different sports and age groups and establishing linear speed and other competencies that should precede COD drills (especially more reactive drills) is warranted, especially for novices and less-skilled athletes (Young, et al. 2014). While one approach to improving reactive agility is to engage in reactive agility training, improvements in reactive agility as the result of such training would still be considered near-transfer, and demonstration of far-transfer to sports performance outcomes are still warranted (Paul, et al. 2016), although improvements in reactive agility performance may be considered "further-transfer" when compared to computerized cognitive tests (Issurin, 2013).

However, in the instance that agility training must be performed in a self-directed manner, it is challenging to create unpredictable, reactive, and perceptual-cognitive demands without external inputs in an accessible manner without tools, environments and technologies that would allow such conditions. This is especially challenging when attempting to translate certain technologies used in research to self-directed, realistic, and sport-specific settings. For example, while small-sided games or scrimmages may be more ecologically valid ways of addressing reactive agility as it relates to sports performance (Young, et al. 2014), this type of training cannot be accessed off-field or with an individual, a smaller number of athletes or within one-on-one training with a coach or team-mate. As another example, while some research has demonstrated the value of anticipatory video-based training for improving reactive agility (Nimmerichter, at al. 2016), accessing this type of training individually, affordably, and in a sports-specific context can be challenging. In addition, providing perceptual-cognitive information coupled with sport-specific actions in relevant contexts may provide better outcomes and transfer to sport in accordance with the theory of ecological dynamics and the modified perceptual training framework.

Test Type	Measures	Reliability	Validity	Laboratory	Use as a training tool
Light Stimuli	Sample Reaction time Response Accuracy	Moderate	Low	Laboratory and filed	Recommended
Video Stimuli	Visual search Decision time Movement time Response accuracy	Moderate	Moderate	Laboratory	Not Recommended
Human Stimuli	Visual Search Decision Time Movement time Response Accuracy	Moderate	High	Laboratory or filed	Less Recommended

Figure 12: Paul, D. J., Gabbett, T. J., & Nassis, G. P. (2016). Agility in team sports: Testing, training and factors affecting performance. Sports Medicine, 46(3), 421-442.

Agility depends upon a variety of factors including anthropomorphic, perceptual, cognitive, technical, motoric, and physical qualities that athletes may possess. Decision-making abilities are included in these characteristics, which involves the ability to determine task-relevant cues and select an appropriate cognitive-motor response. In addition to decision-making abilities being important in agility, the generation of force in coordination with impulse control, the establishment of perceptual-cognitive skills, anticipatory abilities, and visual search abilities seems to differentiate higher-skilled athletes from those that are less skilled (Spiteri, et al. 2018). Incorporating both general and specific cognitive demands into agility training may positively modify sports performance outcomes, however the stimuli within reactive agility likely matters.
For example, movement speed, the presence of object manipulation, and stimulus presentation (including type, timing, and position), accuracy, response times, directional outputs, environment, and equipment utilized all play important roles in the potential efficacy of reactive agility training. A combination of contextual cues, environments, and tasks contribute to the perception-action coupling that is present in both sport and agility training (Spiteri, et al. 2018).

The information-action coupling present in agility training is important to consider, both in considering the fidelity of the information and actions separately, and also simultaneously. It is critical to consider the difference between sports-related information (such as passing a soccer ball) versus cueing (associating a color with a movement). Sports-specific information presents with perceptual-cognitive information associated with the task that possesses sport-specific context (i.e. timing of a ball pass, space between players, people or objects moving in space, etc), while cues may be abstract, non-natural stimuli that do not show up in sporting environments (Renshaw, et al. 2019). However, there may be a “middle-ground” in which sports-specific actions are associated with abstract cues (colors, numbers, arrows) in the absence of more sports-specific information (such as moving persons), although abstract stimuli should seek to better represent sports-specific information as technology and training conditions would allow.

The movements that are executed within perceptual-cognitive and reactive agility interventions should also be designed with sports-specificity in mind. “Action fidelity” could be understood as how valid movements are in the context of ecologically validity in sport, and methods that employ button presses, controller movements, fine-motor responses, positions not encountered in sport (such as static standing, prone, kneeling, or seated positions often used to engage in certain perceptual-cognitive training modalities) are not as valid as sports-specific movements and actions that are representative of sporting environments (Renshaw, et al. 2019, Williams, et al. 2019). Therefore, the actions utilized in reactive agility and perceptual-cognitive training should possess greater fidelity and sports-specificity when designing such interventions so as to enhance the likelihood of transfer to sport. In addition, it is unknown as to whether the selection of irrelevant information and/or actions in such interventions may be less effective, disruptive or potentially decreases in performance in regards to accurate perception-action coupling in sport, which warrants further caution in their design (Willaims, et al. 2019).

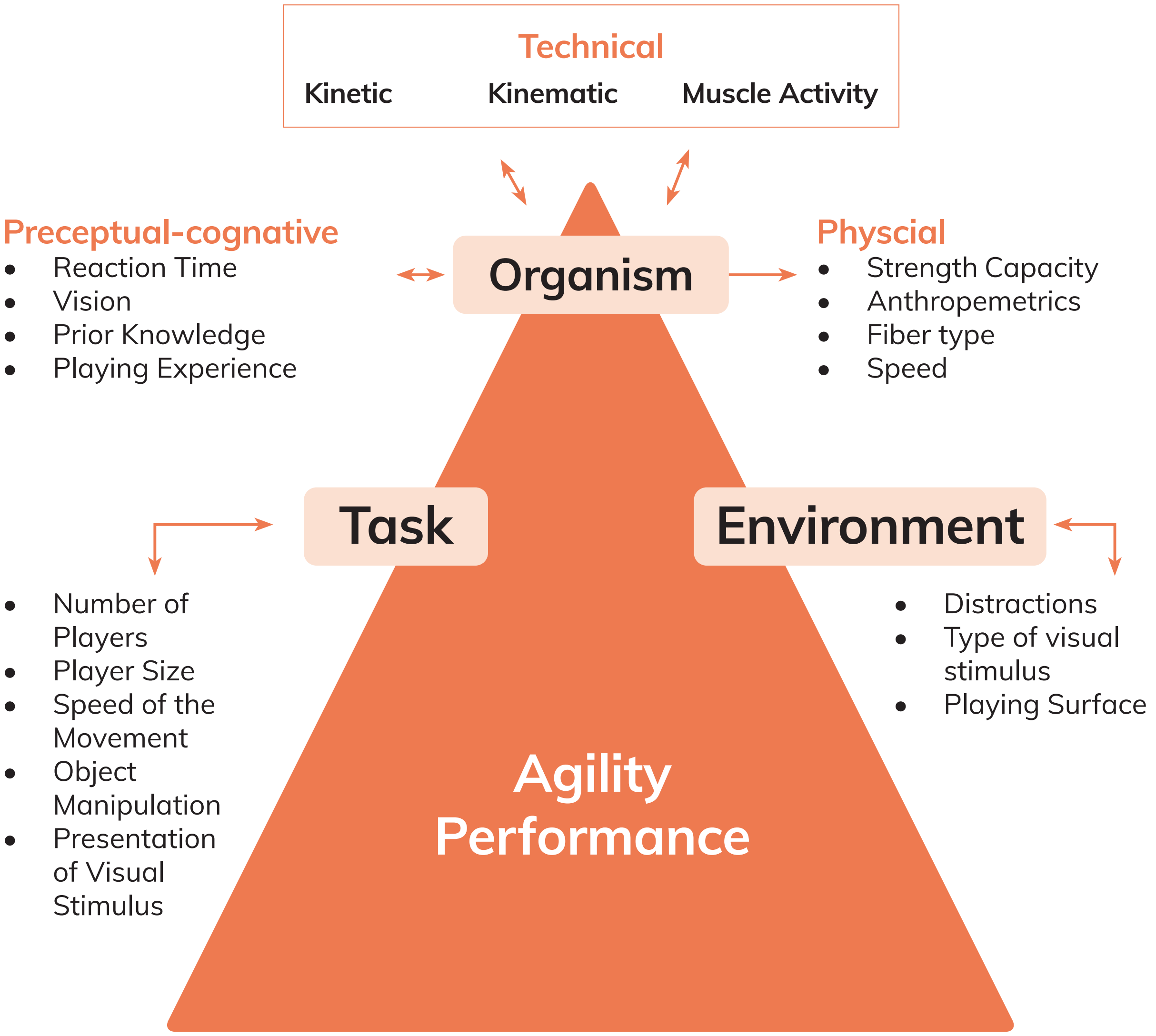


Figure 13: Spiteri, T., McIntyre, F., Specos, C., & Myszka, S. (2018). Cognitive Training for Agility: The Integration Between Perception and Action. Strength & Conditioning Journal, 40(1), 39-46.

Given that a multitude of variables are present within agility training, there are several concepts that make agility training more efficacious, especially when pairing agility training with reactive elements. Movement variability, including multi-directional change of direction (COD) as opposed to predictable and linear or semi-linear movements patterns, in combination with movements that are relevant or encountered in sport, would provide athletes with training in a variety of "motor problems" that may arise within sport (Spiteri, et al. 2018). While the maximization of transfer to sport will be associated with sport-specific stimuli (such as human opponents performing deceptive movements), the use of general, nonspecific cognitive stimuli (lights, arrows, auditory cues, etc) may be helpful for creating reactive environments that can be controlled and paired with sport-specific environments, objects, and movements.

As with dual-tasking, such stimuli may be used as "distractor" information layered with sport-specific movements (which may be helpful for training selective attention, impulsivity, and divided attention), or preferentially integrated with a motor task, such as moving in different directions in response to numbers or arrows, or associating certain sports-specific movements with the working memory demand of associating movements with specific cues to vary perception-action coupling in a more context-specific manner. This "constraints-induced" approach may be efficacious when performing movements that possess action fidelity, and the temporal demands and complexity of a task is imposed upon an athlete to better address perceptual-cognitive-motor skills in athletes (Renshaw, et al. 2019). Such examples may be more efficacious than simply responding to cues or lights in a manner that possesses less cognitive load, performed outside sports-specific environments, and responded to with movements that have little relevance to sport.

Table
Characteristics of COD and agility training methods and their application to programming

	Planned COD movements	Agility activities with generic stimulus	Agility activities with sport-specific stimulus
Examples	Cutting/side stepping, side shuffling, backpedaling. Cones, poles, and ladders may be replaced with "live" obstacles where appropriate	Flashing lights, flashing arrows, coach pointing, and coach calling out direction	Evasive drills, small-sided games.
Main benefits	Development of footwork, balance, and general COD techniques	Provides "time-stress," natural footwork movements	Sport-specific movements, develops perceptual and decision-making skills, holistic development of agility. Good transfer to performance.
Main weaknesses	Can involve unnatural nonspecific footwork, no perceptual and decision-making development	Does not develop perceptual and decision-making aspects of sport, for example, anticipation	Difficult to control agility load (repetitions) for all athletes in games.
Role in athlete development and in a periodized program	Suitable for developing athletes or athletes lacking basic COD technique	Progression from planned COD movements	Well-trained athletes, athletes lacking perceptual and decision-making skill, emphasize in precompetition and competition phases.

Figure 14: Young, W., & Farrow, D. (2013). The importance of a sport-specific stimulus for training agility. Strength & Conditioning Journal, 35(2), 39-43.

Incorporating controlled, general nonspecific stimulus may assist athletes with developing visual search, perceptual-cognitive skills, movement variability, COD, and basic perception-action coupling that may provide better transfer to sport when compared to closed-skill, preplanned agility techniques. Object manipulation demands may also be more efficacious, especially when sports-specific objects are utilized, as demonstrated in reactive agility testing and training (Paul, et al. 2016), although additional object manipulation demands that are nonspecific to sport may be useful in the context of distraction or sports-specific movement integration, especially when the primary visual focus is removed from equipment that may not be relevant to sports scenarios (such as not focusing on agility equipment when moving, but responding to them in sports-specific contexts).

The orientation of visual focus of an external stimulus will default to an athlete's external focus of control, which may affect the speed and accuracy of performance (Singh, et al. 2021, Vignais, et al. 2009), as well as changes to motor control and may modify transfer effects of training to sport (Afonso, et al. 2012, Wulf, et al. 2001), although the majority of this research does not refer to reactive agility training specifically, and such research is warranted. However, Spiteri, et al. (2018) suggests that when a perceptual-cognitive skill and task constraints have been selected, the external focus of athlete's can be directed towards the perceptual-cognitive skill.

This is likely a default among most, if not all, perceptual-cognitive training modalities, as they rely primarily on the processing of information present externally to the athlete.

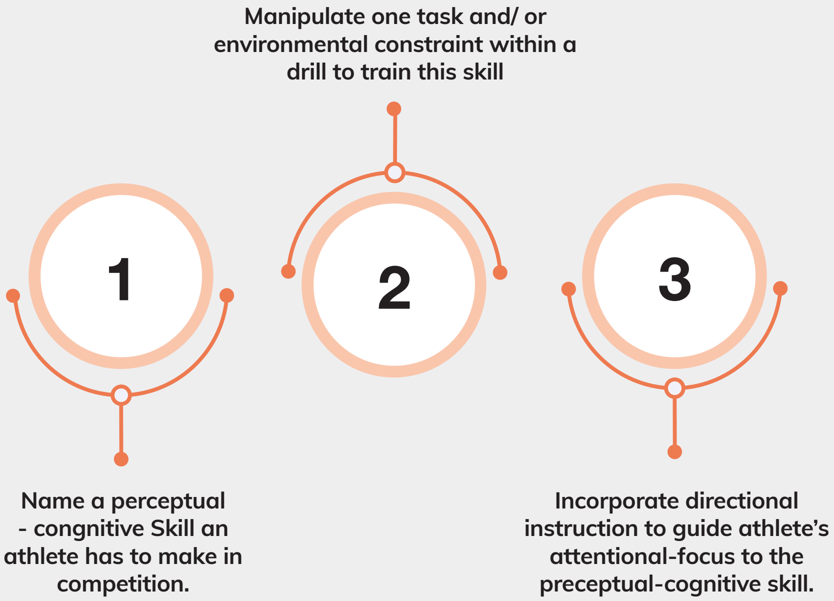


Figure 15: Spiteri, T., McIntyre, F., Specos, C., & Myszka, S. (2018). Cognitive Training for Agility: The Integration Between Perception and Action. Strength & Conditioning Journal, 40(1), 39-46.

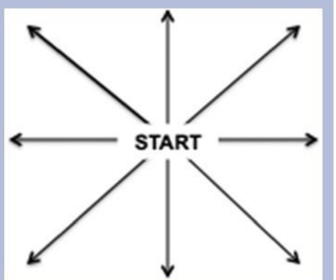
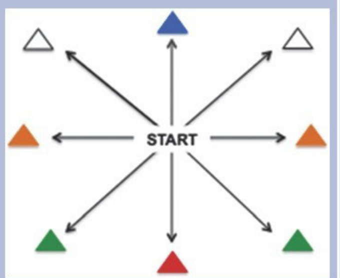
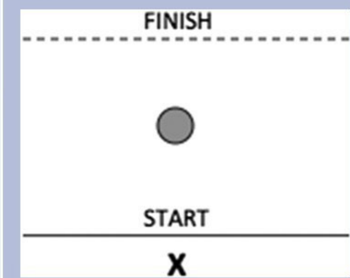
Movements within agility (including reactive agility) are typically quite linear (or semi-linear, as in "Y" formations), but athletes may benefit from various configurations. In addition, in the utilization of visual stimuli, position may be important, as visually-fixating on ground-oriented cues (lights on the ground, agility equipment) may not be as ecologically valid as visually processing cues at eye-level, which is more common in sport. In addition, modifying the presentation of a general cognitive stimulus to provide varied temporal (or timing), spatial (where the stimulus comes from), and cognitive (emphasized domain of cognition, speed, accuracy) parameters can be manipulated to provide greater sports specificity. Structuring these types of drills in a random practice (versus blocked, preplanned practice) format with provision of performance feedback are all elements that may contribute to a more efficacious, controlled reactive agility setting (Spiteri, et al. 2018).

Considering the MPT framework and drawing from the findings and recommendations of research in perceptual-cognitive training, there seems to be various principles and characteristics present in perceptual-cognitive training methods if far-transfer to sport was to be more likely. While generalized, nonspecific cognitive demands (visually or auditorily presented random stimuli) are not entirely sports-specific, they can be performed in a manner that provides a reactive environment with varying levels of cognitive load that is integrated with movements relevant to sport.

In summary, the principles that should be included in reactive agility programs include sport-relevant motor responses, varied movement choices, varied and higher-level cognitive, temporal, and spatial demands, performance in sports-specific environments, the integration of sports-specific equipment, performing within a random practice framework, and progression of perception-action coupling to eventually include sports-specific human interaction. Reactive training, when facilitated with affordable and scalable equipment and technology, provides a promising opportunity to scale closed-skills to more open-skill, reactive settings when highly ecologically valid and sports-specific training is not available.

In addition, reactive training that can be self-directed and accessible while adhering to the aforementioned principles warrants to be made available such that athletes at various levels can participate in more efficacious reactive agility and sports conditioning programs to better increase likelihood of transfer to sport.

Table
Development of agility performance progressing from movement-orientated (basic) to perception-action coupling (advanced) training using a structured practical framework

Training aim	Movement competency and identification of limitations in physical and technical capacity	Create a "controlled reactive setting": training ability to recognize and respond to a stimulus (reaction)	Allow athletes to explore movement solutions in response to a movement problem
Environment	Closed →	→	→ Open
Stimulus type	No stimulus	Introduce nonspecific stimulus (light, whistle, voice commands, and colored cones)	Sport-specific/context-specific stimulus (another team mate) Responding to movement of an object used in the game
Practice conditions	Random practice (order of drill repetition) Part-to-whole practice Manipulate the environment (distance of movement execution) Manipulate the task (speed of movement execution)	Random practice Temporal variability (timing of the stimulus changes) Alter the type of stimulus Time constraints	Random practice Temporal and spatial variability (timing and location of the stimulus) Vary environmental and task constraints
Feedback and cueing	Extrinsic feedback (coach or trainer) KR (outcome of the movement) Cueing: external focus (movement cues)	Extrinsic feedback (start to decrease) Intrinsic feedback (start to increase) KR KP (quality of the movement) Cueing: external focus (movement cues)	Intrinsic feedback KR KP Cueing: external focus (movement and perceptual cues)
Example drill progression	Star drill: emphasis deceleration body control—"stick and hold" on deceleration One repetition forward running One repetition backward pedaling One repetition 45° forward running One repetition lateral shuffle One repetition 45° backward pedaling  *Can manipulate the size of this drill	Reactive star drill: emphasis deceleration body control—"stick and hold" on reactive deceleration Forward running (blue cone) Backward pedaling (red cone) Lateral shuffle (orange cone) 45° backward pedaling (green cone)  *Randomly alternate movement by cueing cone color	Man-on-man drill (space restricted): athlete must perform a variety of directional changes to bypass a defensive opponent and reach the finish line  *Can implement a time constraint, size of the drill, add an object (e.g., basketball), or increase the number of defensive or offensive opponents

KP = knowledge of performance; KR = knowledge of results.

Figure 16: Spiteri, T., McIntyre, F., Specos, C., & Myszka, S. (2018). Cognitive Training for Agility: The Integration Between Perception and Action. Strength & Conditioning Journal, 40(1), 39-46.

Training Dosage

While the benefits of reactive agility, cognitive-motor dual-tasking, and perceptual-cognitive training vary, each possessing their own unique outcomes, a natural question arises in regards to dose response. Many perceptual-cognitive and computerized cognitive training approaches allude to the value propositions associated with off-field training, increasing a certain percentage improvement in performance, with marginal gains accrued with a nominal amount of hours or weeks or training. What is less clear, however, is whether the dose response for certain interventions (such as computerized cognitive training) translate to motor-enhanced or integrated interventions (such as reactive agility training), and what the differences among various populations may be (youth, older adults, novices, experts, etc). Interventions in cognitive training typically seek to be either restorative (restoring lost functions, such as that in stroke or traumatic brain injury), compensatory (training aspects of cognitive to compensate for a lack of effective functioning), or additive (which seek to enhance or optimize existing cognitive functions), in which most perceptual-cognitive training approaches in sport seek to be additive (Harris, et al. 2018). Problematically, many private entities, experts and sports teams accept or incorrectly translate research from compensatory or restorative training methods (which are typically studied in populations with neurological deficits) and assumedly apply such principles to additive forms of training in healthy populations. This is especially problematic when attempting to apply these methods of training to expert athletes, who likely already have higher levels of perceptual-cognitive skills. Regardless, many commercial cognitive training approaches appeal to the value of improving by a smaller marginal percentage (i.e. 1% or 5%), stating that such gains could differentiate themselves on the field among competitors (Renshaw, et al. 2018).

While commercial cognitive training approaches may improve task-specific practice, the dose response required to do so is likely to be much less than the amount of training time required to translate to far-transfer in sport (assuming that a training method would even lead to far-transfer in the first place). As such, some perceptual-cognitive training modalities promise improvements in task-specific practice after only several hours or sessions of training. While these methods may demonstrate task-specific improvements in performance and neurophysiological changes (such as changes in frontal brain activity as indicated by EGG), increases in performance does not necessarily indicate transfer. Another issue associated with identifying the ideal dosage of training stems from small sample sizes, issues with identifying tests of retention, a lack of long-term follow-up or longitudinal studies, a lack of replication of research, and a lack of using tests that demonstrate sufficient transfer (Harris, et al. 2018).

However, in a systematic review of decision-making training in volleyball athletes, it was found that utilizing various methods of perceptual-cognitive training (video training, 3D multiple object tracking, etc), interventions varied between 4 and 13 weeks in duration, with the number of sessions ranging from 8 to 26 sessions, with session lengths ranging from 10 to 60 minutes.

Some training methods were also conducted consecutively with sports-specific practice or sports conditioning (Conejero Suarez, et al. 2020). Another study of Australian-rules football athletes performed small-sided games (SSG) or COD training 1-2 fifteen minutes sessions per week, with approximately 11 sessions performed over 7 weeks. Although SSG was found to be more effective than COD training in tests of reactive agility, more research is needed to determine if COD and/or reactive agility training may need to possess certain characteristics or increase their “dosage” of frequency, intensity, duration or complexity in order to better improve sports-performance outcomes (Young, et al. 2014).

Another systematic review and meta-analysis of SSG training found that most interventions lasted anywhere from 4 to 12 weeks, with the majority lasting 6 to 8 weeks. Sessions were performed approximately twice per week at about 80% of maximum heart rate (MaxHR). Based on this review, a minimum of 4 weeks of training was recommended, with 8 weeks being the average, and 12 weeks recommended in youth sports to allow for optimal adaptation (Hammami, et al. 2018). Lastly, dual-task or exergaming training interventions for older adults have been recommended to be at least 12 weeks of at least 60 minutes per week to lead to significant improvements in executive functioning and processing speed (Stanmore, et al. 2017), although caution should be implored when attempting to translate these findings to athletes who likely already possess higher levels of perceptual-cognitive skills, executive functioning, and processing speed (Voss, et al. 2010). Regardless, these metrics may be helpful when attempting to periodize reactive agility training and perceptual-cognitive-motor interventions.

Periodization is routinely utilized in strength and conditioning literature and programs to express the frequency, intensity, time, type, and program duration required to elicit specific adaptations. While the periodization framework is widely adopted for strength and conditioning programs, skill-development lacks any specific periodization framework. As such, perceptual-cognitive methods are typically utilized without specific structure or planning, and are often “tacked on” to existing conditioning programs as a novel form of training. However, it may be beneficial to periodize methods such as reactive agility and perceptual-cognitive training in a similar manner to how skill-development may be periodized for high-performing athletes (Farrow, et al. 2017). In order to propose a structure for the periodization of skill development, Farrow and Robertson (2017) have proposed the specificity, progression, overload, reversibility, and tedium (SPORT) acronym to provide a framework for this approach.

The Specificity in SPORT is reflective of the demands experienced in sport and competition. This is relevant to ecological validity and representative learning design, and is important considering most laboratory experiments and perceptual-cognitive training approaches feature simple or non-specific tasks that can be learned in a very small amount of time. While these experiments may partially differentiate novices from experts, programming for skill development requires a consideration of an athlete’s unique capacity for attention and technical proficiency. A part of specificity includes the “overload principle”, which is recognized in strength training literature, but less explicitly utilized in skill training. Specificity can utilized with overload and random practice in a variety of ways, such as reacting to a stimulus with sport-specific action(s) within a variety constraints, such as reacting within less than 1 second, between 1-2, 2-3, and 3+ seconds, and by placing a certain number of reps to be distributed across various reaction times while tracking accuracy and cognitive load (Farrow, et al. 2017).

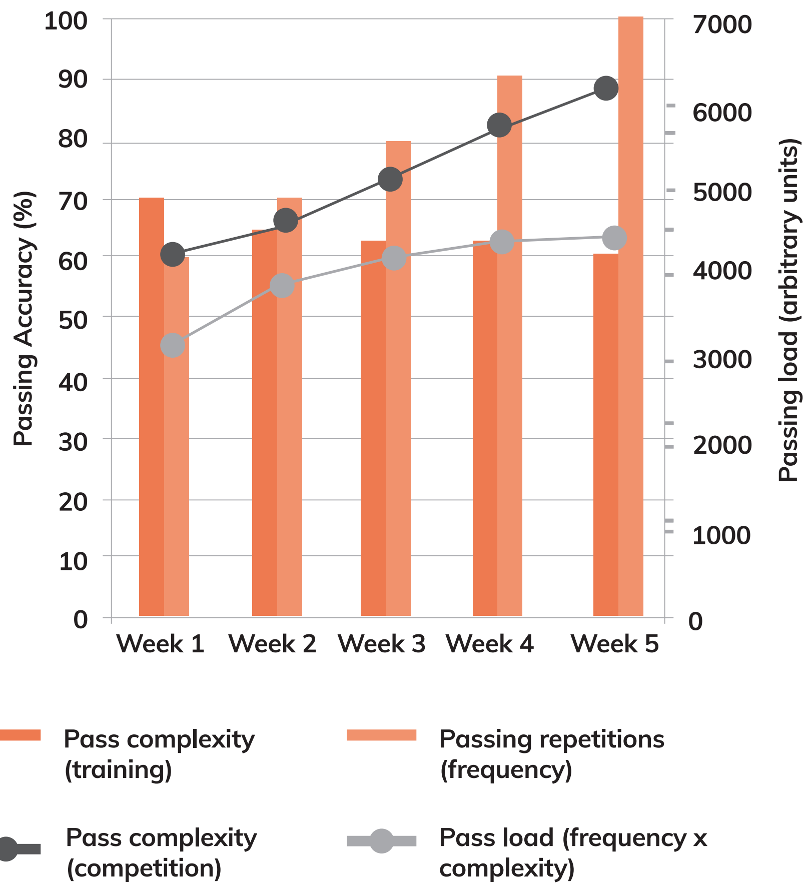


Figure 17: Farrow, D., & Robertson, S. (2017). Development of a skill acquisition periodisation framework for high-performance sport. Sports Medicine, 47(6), 1043-1054.

In tandem with utilizing the overload approach, the Progression aspect of SPORT refers to an athlete's capacity to tolerate increased skill-demands (or skill "load"). While load in resistance training can be defined in weight, reps and sets, skill load may be understood as increases in technical demands, greater amounts of practice specificity, increased speed demands, increased allocation of attention (as seen in deliberate practice), and/or higher levels of cognitive demands. In terms of skill load, higher levels of frequency and intensity may be understood as greater task "complexity", which will increase error and cognitive demands, which are more likely representative of sport (Farrow, et al. 2017). In order to gauge cognitive (or mental) demands or complexity, a rate of perceived exertion (RPE) scale can be used in a similar manner it is utilized for physical intensity. The steady increase in psychomotor speed (also utilized in overspeed training), complexity, contextual interference, cognitive effort, and a greater reliance on random practice (which will decrease performance but more likely transfer to sport) is alluded to in the Overload principle of SPORT (Farrow, et al. 2017).

The reversibility in SPORT refers to the principle of losing training benefits when relevant training activities are reduced or stopped. While the cognitive benefits of skill-learning may be enduring (Tomporowski, et al. 2019), higher levels of skill acquisition and refinement may degrade in performance if they are not maintained, although the specific timing considerations for reversibility are not concrete.

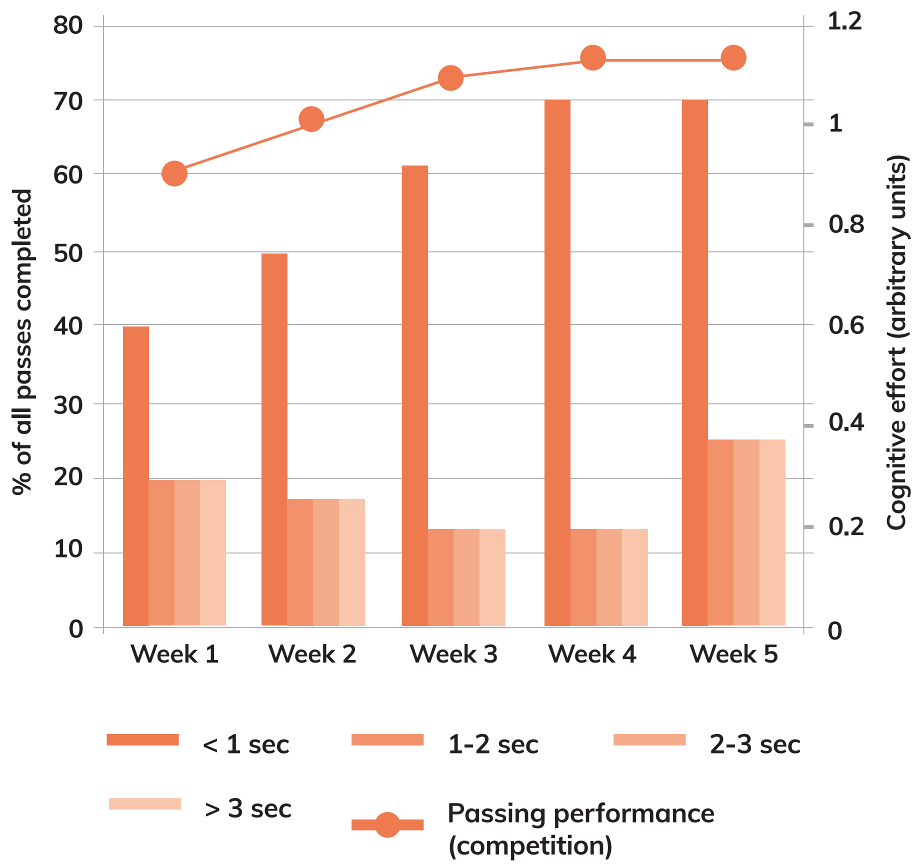


Figure 18: Farrow, D., & Robertson, S. (2017). Development of a skill acquisition periodisation framework for high-performance sport. Sports Medicine, 47(6), 1043-1054.

The utilization of transfer tests, retention tests, subjective accounts (such as perceived subjective performance or perceived levels of fatigue among previously-encountered demands) may contribute to better understanding reversibility. Similar to resistance training or aerobic conditioning programs, "de-loading" phases and sound recovery behaviors (such as healthy sleep quantity and quality) may be beneficial for the consolidation of skill-based memories (Farrow, et al. 2017). By better understanding reversibility, practice and perceptual-cognitive training methods can be employed with a periodization framework to minimize reduced performance and better assess if and how marginal gains can be translated to sport.

The tedium (being in state of "tedious") in SPORT refers to the potential state of boredom experienced by athletes due to monotonous approaches to skill development that may be detrimental to the outcomes of any given skill-development program. Training variables such as intensity, complexity, variability, frequency, time, and specificity can be manipulated to avoid tedium, and motivational, psychological, and team-based strategies can be synergistic to these approaches. For example, variable and random practice can decrease tedium in comparison to constant or blocked practice, the latter of which emphasizes "getting in reps" of the same movement pattern, which is less likely to be effective. Tasks can also be modified to better represent the sports environment, which will possess greater complexity and variability.

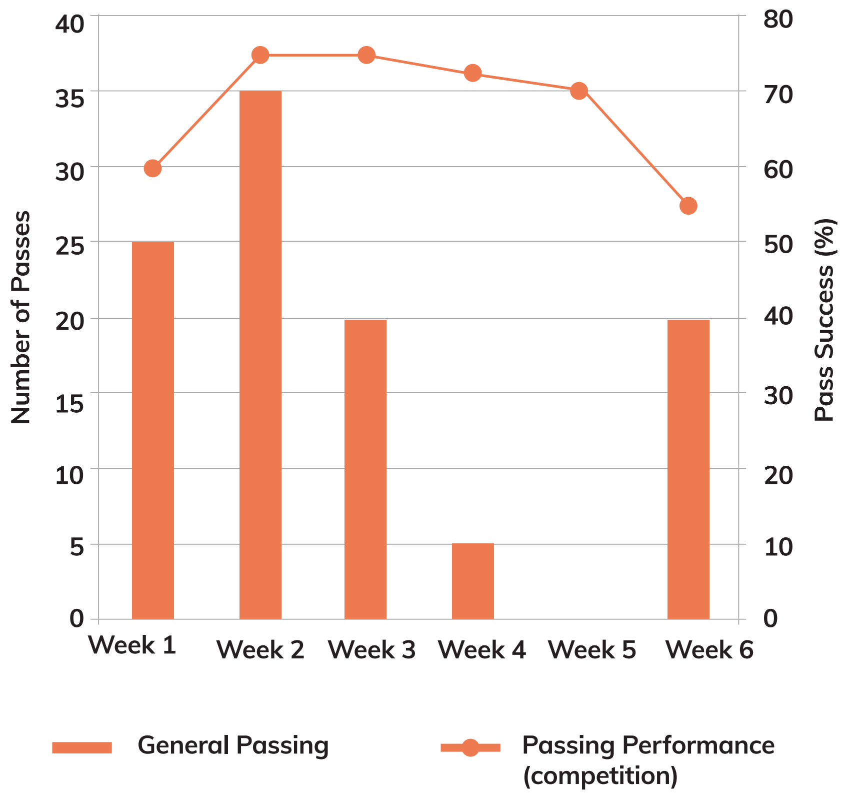


Figure 19: Farrow, D., & Robertson, S. (2017). Development of a skill acquisition periodisation framework for high-performance sport. Sports Medicine, 47(6), 1043-1054.

Cognitive load can also be modified to reduce tedium by progressing simple and low cognitive load tasks to tasks with greater cognitive difficulty (or complexity) and higher cognitive demands (Farrow, et al. 2017).

However, in modifying these approaches to reduce tedium, practitioners must recognize the skill-level of the learner so as not to create frustration, as indicated by the Challenge Point Framework (Guadagnoli, et al. 2014).

Tedium continuum	HIGH				LOW
Skill practice approach	Constant practice	Blocked practice	Variable practice	Random practice	Differencial practice
	Repeat the same skill in the same manner on each repetition	2 or more skills practised in blocks (i.e., kick, kick, kick, volley, volley, volley)	Vary the one skill via changes in distance, force etc.	2 or more skills randomly interpersed across practice (kick, volley, volley, kick…)	Vary the one skill every practice repetition (i.e., kick using different approaches to the ball)
Environmental demand	Low representative / controlled / drill		Semi-controlled / drill-game		Representative / open-ended game
	No defence		Passive defence		Active defence
	Unrestricted time in ball possession		Time limted ball possession		Severe time limits on ball possession
	Large amount of playing space		Reduced playing space		Varying playing space
Cognitive effort / load	SIMPLE LOW				DIFFICULT HIGH
Performer	UNSKILLED				SKILLED

Figure 20: Farrow, D., & Robertson, S. (2017). Development of a skill acquisition periodisation framework for high-performance sport. Sports Medicine, 47(6), 1043-1054.

In summary, the SPORT acronym can be utilized, at least in part, to better guide the periodization of skill development, and perhaps perceptual-cognitive training methods including reactive agility, recognizing that there are similarities in the information processing, acquisition, and consolidation processes associated with both approaches. While the SPORT framework provides many complexities within its structure, it is helpful to acknowledge these variables beyond the simplicity of allocating simple blocks of time to skill development or other perceptual-cognitive training approaches.

In regards to decision-making and perceptual-cognitive training approaches, a generalized range of 4 to 12 weeks of training, for a total of 8-26 sessions of 10 to 60 minutes in duration at a moderate to vigorous physical and cognitive intensity may serve as "working guidelines" for periodizing these approaches.

However, this is difficult to gauge given the large number of variables present in consideration of the potential effectiveness of these methods (Farrow, et al. 2017), and in whom, as well as what dosage best serves far transfer and supersedes reversibility in athletes.

Conclusion

Through utilizing the “expert approach” in research, high performing athletes seem to possess higher levels of perceptual-cognitive skills and neurophysiological characteristics that differentiate them from novices and non-athletes. Computerized cognitive and perceptual-cognitive training approaches seek to target and enhance these skills through the “process training approach”, and while they have demonstrated improvements in performance on task-specific and near-transfer tests, the vast majority of these approaches have yet to demonstrate sufficient far-transfer to sport. The “ecological dynamics approach” criticizes these methods for not better representing the complex and variable demands of sports, and not possessing the cognitive and physical validity of sports-specific training. In addition, the field of cognitive-motor dual-tasking has demonstrated potential value in improving the cognitive and/or motor skills of athletes and clinical populations. Reactive agility training can combine aspects of the process training, cognitive-motor dual-tasking and ecological dynamics approaches, by combining generic cognitive stimuli that are simultaneously executed with sports-specific movement skills in sport-specific environments that can range in various complexities and temporal (or speed) demands. This approach to agility training may provide an advantage over computerized perceptual-cognitive training approaches that do not translate to the field or incorporate ecologically valid sports-specific movements, expensive devices that possess only abstract stimulus that is less relevant to sport, pre-planned and closed-skill agility training, and self-directed training approaches that do not possess the complexity and variability of externally-paced sports-specific training. Principles derived from the ecological dynamics approach, the modified perceptual training framework, the SPORT acronym for the periodization of skill development, and the dose-response patterns within perceptual-cognitive training approaches should be considered when implementing methods such as reactive agility training if improved transfer to sport was to be desired.

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