Physical Activity and Cognition

The What and the Why

How do we explain the relationship between physical activity and cognition? For the past several decades research has been investigating this relationship to better understand its underlying nature as well as what mechanisms may be responsible.

Topics: Expert Performance approach — Cognitive Component Skills approach — Near vs Far Transfer — Cerebellum Theory — Top Down Perspective — Selection Bias — Reserve Theory — Behavioral Causality — Reverse Causality — Cardiovascular Fitness Hypothesis — Cognitive Training Hypothesis — Health Neuroscience — Angiogenesis — Neurogenesis — Adaptation — Exaptation

Like many areas of kinesiology, research on the effect of exercise and physical activity behaviors on cognition began with a primary focus on trying to understand those factors that contribute towards elite sports performance. The idea being that if we understand the unique cognitive characteristics of elite athletes that we could more easily identify athletes with cognitive abilities that would allow them to become elite (i.e., selection). Further, we could engage in programs to help athletes develop more "elite" like cognitive abilities (i.e., training).

A prominent modern example of this is the growing utilization of light-based sport training systems. Such systems are often promoted under the idea that **elite athletes exhibit faster reaction time and more rapid visual search processes than novice athletes and the general public**. The premise is that these abilities can be identified and trained by arranging touch sensitive light pads across the athletes visual field. When a light pad is randomly turned on, the athlete must then move to push the light pad and deactivate it. Given the relatively low cost of these systems, they have become a staple of sports enhancement and athletic training facilities.

At a basic level, the idea of rapidly responding to a cued target corresponds well with the construct of motor speed. Having more than one light pad that could provide the cue requires a very wide spread of executive attention. Multiple potential light pads and colored cues requires aspects of decision making (i.e., information processing). Depending upon the instruction of how to respond based upon the way the light pads turn on, it is even possible to create situations that require cognitive control (e.g., respond to one color, inhibit a response to another color; changing response patterns based upon the color or target). But the key question is if they actually provide a benefit for selection or training.

Expert Performance approach — Studies the athlete under a sport-specific, or an ecologically valid, context.

Cognitive Component Skills approach — Studies the athletes abilities on core cognitive skills or abilities, free of sport specific context.

To answer that question, it is helpful to understand that much of the early work in this area utilized the **Expert Performance** approach which specifically assessed athletes in sport-specific context. For example, soccer players would be briefly shown images/videos of soccer-specific situations and then would be asked to make decisions such as who has the ball, are they going to pass or shoot, who are they most likely to pass too. Unsurprisingly, elite level soccer players consistently perform more accurately on such tasks, being able to make such decisions not only more quickly but also requiring substantially less viewing time to do so than novice soccer players. Across a wide variety of sports, elite level athletes exhibit superior decision-making and spatial relational memory, and exhibit faster visual search for sport-specific environmental information.

More modern work in this area has begun utilizing the **Cognitive Component Skills** approach to specifically focus on the underlying cognitive abilities that may enable athletes to exhibit such superior performance. The key question in this approach is trying to understand why an athlete might exhibit superior performance in the sport specific context and if it is due to generally superior cognitive ability in a domain or rather is specific to the athletes environment of expertise. For instance, in the example of showing soccer players images/videos of soccer-specific situations, consider the very nature of decision making processes (i.e., information processing). An athlete who has frequently been exposed to particular sport specific context is likely to have learned associations between particular situations and their associated actions. As a result they are likely able to rely upon the habit system (Type 1 processing) for action-selection — a system characterized by being particularly fast and efficient.

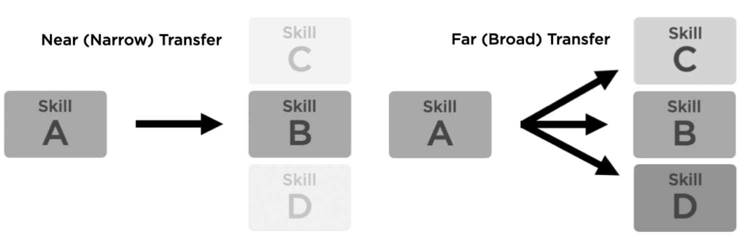
A novice athlete may only have minor familiarity with the context and thus would have to rely upon the deliberative system (Type 2 processing) to determine the various alternative outcomes and potential risk-reward relationships. This system is characterized by slow and effortful processing. So faster performance in this circumstance would be expected for the elite athlete simply because they recognized the situation, not necessarily because they have faster motor speed or superior visual search processes. Only by specifically assessing these abilities in context–independent circumstances can we actually know if motor speed and visual search processes are faster.

Near Transfer — Learning and/or performance in one context has an influence on learning and/or performance on highly similar movement patterns or skills.

Far Transfer — Learning and/or performance in one context has an influence on learning and/or performance even for dissimilar movement patterns or skills.

To further complicate the matter, we also have to consider the similarity of the training to the actual task and how the training would transfer (i.e., apply) to the sporting environment. Training that only transfers to very similar movement patterns or skills is considered to have **Near Transfer** (also sometimes called Narrow Transfer), whereas training that broadly improves performance across a wide range of movement patterns or skills is considered to have **Far Transfer** (also sometimes called Broad Transfer). For instance, having an athlete practice jumping from a loaded stance when they hear an auditory tone would be highly similar to the real world situation of a sprinter coming out of the starting blocks. But such training would likely have minimal impact upon any of the other movement patterns/skills/performance beyond the start of the race. Such training would thus be considered to have Near Transfer. Unfortunately, regardless of how aspects of cognition are trained, the evidence indicates that cognitive training has very near transfer. While the individual may get better at the specific activity they are doing, that benefit has very little transfer beyond that specific activity.

Figure: Transfer Patterns.



We can also consider the extent to which training could have a negative impact on related skills. If practice on one thing improves performance on another it is considered to have **positive transfer**; while if practice on one thing causes performance to deteriorate on another it would be considered to have **negative transfer**. 1970's era strength and conditioning approaches used to specifically recommend against athletes engaging in strength training of their lower body because the increases in strength/muscle mass were associated with slowing of their movement speed (i.e., negative transfer effects of strength training).

So in the case of light-based sport training systems, we have to consider the context of the evidence justifying their use as well as the potential transfer of the way the training is implemented. While elite athletes do tend to have faster motor speed than novice athletes across a wide assortment of contexts; differences in visual search processes appear to be unique to sport-specific environmental information. When implemented in ways to promote more rapid motor responses or encourage agility, these training systems have been found effective if the training very closely mimics the sporting environment as it has Near Transfer. However, such reflexive training with these devices has zero transfer outside of these domains and can even negatively impact performance situations were athletes must "read" an opponent — as responding to different colored lights has no contextual relevance to the sporting situation. Thus, while often touted as cognitive training, there is little evidence for cognitive benefits beyond motor speed — but since motor speed is technically a domain of cognition, the statement on cognitive benefits is technically true.

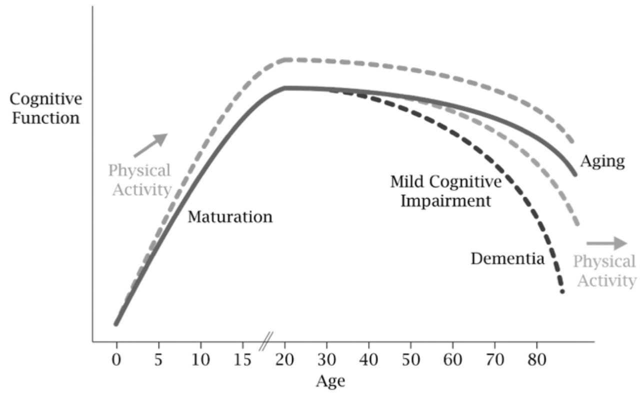
Cognitive Effects of Chronic Engagement in Physical Activity

A prominent finding from early work in this area was that older elite athletes exhibited a tendency to show less age-related dysfunction than older non-athletes. Given the consistent evidence showing faster motor speed and information processing among elite athletes, much of the early work in this area adopted a **Bottom Up** perspective. Part of the conceptual justification for focusing on what have been termed "low-level" cognitive processes (such as simple motor speed/learning or information processing) was based upon the assumption that the reason elite athletes showed faster motor speed and information processing was that these skills were practiced and trained through their sport participation. Sporting environments tend to emphasize and require more rapid decision making and action initiation. So from a dynamic capacity perspective, these abilities should become enhanced and able to be retained to a greater extent with greater sport participation. Therefore, the lack of age-related decline in motor speed and information processing was thought to have occurred in response to characteristics of their training.

However, as research in this area continued to advance, large scale epidemiological investigations began to observe that **the extent to which an individual engaged in chronic physical activity behaviors appeared to be more relevant for cognitive function than if they were a current or former athlete**. Across a number of epidemiological investigations, chronic physical activity behaviors appear to reduce the likelihood of developing mild cognitive impairment and dementia. Adopting an endpoint perspective of sedentary behavior; engaging in higher levels of physical activity was associated with a 38% reduction in the risk of cognitive decline relative to those who are sedentary, while engaging in low and moderate levels of physical activity was associated with a 35% reduction in the risk of cognitive decline. So really the evidence indicates it is not so much about engaging in greater amounts of physical activity but rather **avoiding very low levels of chronic physical activity**. When using accelerometry based measures of chronic physical activity behaviors — which lend themselves to an endpoint perspective of sedentary behavior, individuals who exhibited the lowest levels of physical activity (e.g, those at or below the 10th percentile) were more than twice as likely to develop dementia as compared to those who engaged in more physical activity.

Given the nature of epidemiological investigations which assessed these relationships in thousands of individuals, the assessment of cognition in these studies was rather rudimentary and relied upon measures of global cognitive functioning or dementia screening tools. As a result, initial conclusions suggested that the relationship between chronic physical activity behaviors and cognition was restricted only to older adults, with minimal relationships observed for middle aged adults (35 to 60) and no effects for young adult populations. When considered in the context of **saturation** effects, it should come as no surprise that the finding would not be observed within young adult populations. If assessments are being done using very broad measures of cognition or dementia screening tools; the measure may lack sufficient sensitivity to detect differences. Given the high performing nature of young adults, even those who do minimal activity should still not make any errors on a dementia screening tool (i.e., **ceiling effects**). When the relationship between chronic physical activity behaviors and cognition is assessed using more appropriate and sensitive tools, **engaging in physical activity has been associated with superior cognitive abilities across a wide range of cognitive domains (e.g., academic performance/achievement test scores, multiple domains of cognition, workplace performance) and age groups**. Compellingly, lower levels of physical activity before the age of 18 were the most predictive of development of cognitive impairment later in life — suggesting a role of physical activity in primordial prevention of mild cognitive impairment and dementia.

Figure: Effects of physical activity in the prevention of Mild Cognitive Impairment and Dementia.



Cerebellar Theory — Superior cognitive function and lower incidence of age–related cognitive decline in those with greater chronic physical activity participation is the result of the beneficial effects of activity on the cerebellum.

The cerebellum is an area of the brain located in the back of the head just above the brainstem that is critical for supporting balance, coordination, and complex motor functions. As such, there is a strong bi–directional relationship between activity participation and the functioning of the cerebellum — when the cerebellum is poorly functioning the ability to be physically active can become compromised, and physical activity participation can positively influence neural plasticity in this brain area. Thus, **cerebellar theory** is often suggested as a mechanism that could allow more active individuals to exhibit faster motor speed and generally greater cognitive performance as most cognitive assessments rely upon the speed of a behavioral response. However, the cerebellum is also involved in supporting aspects of cognitive function by coordinating and preparing neural responses. Therefore if the cerebellum is more highly advanced, it would allow for the individual to better coordinate aspects of attention and information processing which would result in superior cognitive function and lower incidence of age–related cognitive decline.

Top Down Perspective — Idea that high-level cognitive and memory operations should be the most reactive to systemic changes to protect the integrity of the organism.

One of the most prominent findings, however, is that while chronic physical activity participation relates to superior performance on low-level cognitive processes; the effect of such participation is even greater for high-level cognitive operations such as cognitive control and memory. Thus, the general evidence indicates that there is a general yet selectively larger influence of chronic physical activity engagement for high-level cognitive operations. Such observations lead to the adoption of the **Top Down** perspective. This top down perspective adopts the view that the very nature of these high-level cognitive operations being critical for effective day to day function is what makes them the most reactive to changes in bodily functioning. These cognitive operations are dynamic and regulative in nature and as a result they are also particularly expansive in their energetic requirements. Thus, if metabolic/energetic systems cannot properly meet their needs, it would be natural to expect diminished functioning. Because low-level cognitive processes are the least energetically demanding, there is not a compelling biological drive to alter their functioning when metabolic/energetic systems are constrained — because doing so would have minimal overall impact.

So is this why consistent findings indicate that high school athletes (as a group) receive better grades than nonathletes, and they have higher academic aspirations? Ignoring the extent to which this could be influenced by sympathetic teachers awarding higher grades to athletes to keep them athletically eligible, it is important to acknowledge that these findings may be the result of two prominent factors. Beyond the benefits of physical activity for developing and supporting cognition; the prominent argument made by schools and parents arguing for schools to adopt particular sports is that **athletic participation builds discipline, strong work ethic, and teaches achievement orientation**. These qualities can be applied to academics and enables those students to achieve better grades and exhibit higher academic aspirations.

However, the most likely explanation for this is that these findings reflect a **Selection Bias**. Athletes may have higher GPAs due to the fact that they must meet minimum standards to be eligible to play. This means that some athletes with poor academic performance are not allowed to play and thus are classified as non-athletes. So if we assume that athletes and non-athletes start with a similar grade distribution. The minimum eligibility standards would take any athletes below the required level and classify them as non-athletes. Mathematically this would cause non-athletes to exhibit lower GPAs simply as a result of

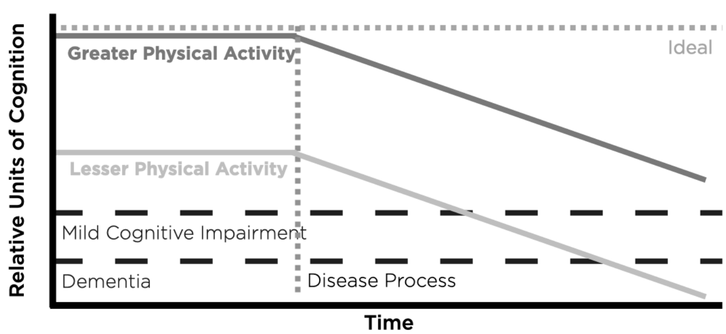
GPA being the selection criteria. Any time a metric is used as both the selection criteria and then argued as a potential benefit of participation (e.g., private schools) then it is important to acknowledge the effect of the selection bias.

What is the Mechanism for these Relationships?

Reserve Theory — Superior cognitive function and lower incidence of age-related cognitive decline in those with greater chronic physical activity participation is the result of a protective buffer provided by underlying alterations in cognitive processes and brain structures.

Reserve Theory is employed as an underlying basis for the observation of superior cognitive function and lower incidence of age-related cognitive decline in those with greater chronic physical activity participation. The idea being that if the cognitive reserve is sufficiently large — conferred either because of greater functioning of cognitive processes or support within neural structures — then the function of a given system is less likely to diminish to clinically significant levels (i.e., meet diagnostic criteria for mild cognitive impairment or dementia) when the disease process occurs. However, that same disease process is likely to result in clinically significant declines in cognitive function in an individual with very little reserve (such as an individual with low levels of physical activity).

Figure: Reserve Theory of Physical Activity and Cognition.



Behavioral Causality — Idea that the relationship between a behavior (e.g., physical activity) and an outcome (e.g., cognition) is causal such that the behavior drives the outcome.

Reverse Causality — Idea that the causal relationship between a behavior (e.g., physical activity) and an outcome (e.g., cognition) is flipped such that the outcome drives the behavior.

Given the cross sectional nature of much of this epidemiological research, it is critical to consider the causal relationships being assumed. From a dynamic capacity perspective the classic assumption is of **Behavioral Causality**, suggesting that engagement in habitual physical activity behaviors was beneficial for cognitive health — ultimately resulting in improvement of cognitive abilities and in particular cognitive control. Therefore, we should get people to be more active to enhance their cognitive abilities.

However, it is equally likely that **Reverse Causality** could have occurred. Pre-existing differences in cognitive abilities may have enabled those individuals with superior cognition to sustain habitual physical activity patterns to a greater extent. Conceptually, this idea of reverse causality applies well when considering the nature of high-level cognitive abilities such as cognitive control. An individual with high cognitive control abilities is fundamentally better at planning, goal setting, and maintaining goal-oriented behaviors.

So an individual with high cognitive control abilities would likely be better able to sustain physical activity behaviors, whereas an individual with low cognitive control abilities would be more likely to drop out of a physically active lifestyle. Indeed, individuals with low levels of cognitive control during childhood are more likely to become obese later in life, and adults with low levels of cognitive control are more likely to exhibit reduced balance, grip strength, and gait speed later in life — screening indices of pathological deterioration of muscle tissue often linked to a lack of physical activity. Thus, efforts oriented towards enhancing cognitive control abilities may enable individuals to sustain more physically active lifestyles.

Longitudinal research indicates that although there is a bi-directional relationship between high-level cognitive abilities and chronic physical activity behaviors; **engaging in physical activity interventions (approaches designed specifically to increase physical activity behaviors) promotes a general facilitation in cognitive performance with a selectively larger benefit for aspects of cognitive control and declarative memory**. Much of the interventional research has contrasted the potential benefits of aerobic exercise training against non-aerobic stretching and toning training. It is important to acknowledge that some of this is simply a function of carrying over interventions in older adults oriented towards improving cardiovascular health — reducing the need to develop new physical activity interventions; as well as a reflection on the relative ease of promoting wheel running in rodent models. Nevertheless, the underlying justification for this was due to the **Cardiovascular Fitness Hypothesis**.

Cardiovascular Fitness Hypothesis — Superior cognitive function in those with greater chronic physical activity participation is the result of greater cardiovascular fitness.

The brain, like muscle tissue, requires energetic resources to effectively function. An individual with superior cardiovascular fitness exhibits a greater ability to efficiently generate and utilize metabolic resources. Therefore, an individual with superior cardiovascular fitness would potentially be able to allocate more energetic resources towards cognitive processes and could sustain energetically demanding cognitive processes (e.g., high-level cognitive operations) to a greater extent than an individual with poorer cardiovascular fitness. This hypothesis therefore matches well with the data indicating a smaller benefit of chronic physical activity engagement for low-level cognitive operations which are less energetically taxing; and a larger benefit for the most energetically taxing aspects of cognition. Further, this idea maps well onto the resource pool theory of cognitive aging in explaining why older adults with greater aerobic fitness exhibit superior cognitive abilities and less age-related cognitive decline. The greater aerobic fitness confers an ability to more efficiently generate and allocate resources to support cognitive processes.

Evidence from cross sectional studies has consistently revealed a strong relationship across the lifespan — when appropriate cognitive assessments are used — that greater cardiovascular fitness relates to superior function of cognitive control and declarative memory processes. Consistent with the cross sectional research, aerobic exercise interventions also appear to positively attenuate (reduce) age-related decline in cognition and promote enhancements in cognitive control and declarative memory. However, a consistent finding is that these beneficial effects are unrelated to the extent to which the intervention was able to induce changes in cardiovascular fitness. Such an observation appears to conflict with the Cardiovascular Fitness Hypothesis. Ultimately, the evidence indicates that while aerobic exercise is beneficial, it is not necessary to incur cardiovascular adaptations to observe a benefit for cognition — regardless of how energetically demanding the aspect of cognition. It is important to note however, that there remains some question in this area given the relatively minimal changes in cardiovascular fitness than can be achieved over the course of a typical 8 to 12 month intervention period. Thus, it may be that the lack of a relationship with cardiovascular fitness is due to **floor effects** in the change in fitness measures.

Cognitive Training Hypothesis — Superior cognitive function in those with greater chronic physical activity participation is the result of physical activity serving as a form of cognitive training.

Another perspective on this area of research is that the beneficial relationship between physical activity engagement and cognition is simply a reflection of cognitive training. The **Cognitive Training Hypothesis** considers these relationships similar to the context of **reverse causality**. Sustaining habitual physical activity patterns requires considerable high-level cognitive abilities. If a sedentary individual was to begin engaging in a more physically active lifestyle, they would have to regularly engage cognitive control processes such as planning, goal setting, and suppressing dominant tendencies (i.e., discipline) in order to maintain behaviors oriented towards their goal. Similarly, acquiring these more physically active behaviors would engage aspects of declarative memory to acquire new information about movement patterns, spatial relationships, environmental awareness, and previous behaviors.

Therefore, the **Cognitive Training Hypothesis** suggests that the very nature of working to become more physically active acts as a form of cognitive training. Consistent with the idea of the dynamic capacity perspective, aspects of cognition that are trained adapt to become better. Although cognitive training typically exhibits near transfer; in this case, the training fundamentally aligns with the aspect of cognition so it should provide a benefit to those cognitive domains more broadly.

In the context of the **Cognitive Training Hypothesis**, engaging in aerobic exercise training might provide greater cognitive benefits than stretching/toning exercises simply because it is more effortful to sustain those behavioral patterns — requiring greater high-level cognitive processes to maintain. A key characteristic of cognitive training is that it only works if it pushes the individual to the limits of their cognitive ability. As a result then, the way in which the physical activity intervention is designed and implemented becomes critical in regards to the extent to which it might induce cognitive benefits or prevent age-related cognitive declines.

Aerobic exercises implemented in contexts where the individual has little autonomy over sustaining the behavior, has little need to remember what to do and when to do it, and in an environment that requires no relational memory to recall where the individual is or needs to go; is ultimately likely to have minimal benefit. Whereas, activities which might require considerable engagement of cognitive control and declarative memory would be expected to show superior benefits. In this way, some argue that health promotion efforts oriented towards supporting cognition and avoiding age-related cognitive decline would benefit from shifting away from the aerobic exercise emphasis and instead emphasize activities such as dance, martial arts, and novel (new) games/activities. Similarly, given the bi-directional relationship between high-level cognitive abilities and chronic physical activity behaviors; efforts to increase physical activity behaviors would benefit from aligning activities with those that increase perceptions of joy, feelings of social support and belonging, and build confidence as these each have been observed to positively benefit both cognitive control and declarative memory. In doing so a positive feedback loop could be created.

Research in the area of **Health Neuroscience** has specifically focused on the underlying neurobiological mechanisms which may contribute towards the relationship between physical activity and cognition. Converging evidence indicates that the neural structures and networks that support cognitive control and declarative memory appear to be particularly sensitive to chronic physical activity participation and the lack thereof. Specifically, research has observed that physical activity interventions in older adults appear to disproportionately influence aspects of the prefrontal cortex including the dorsolateral prefrontal cortex and anterior cingulate cortex, the basal ganglia, as well as aspects of the temporal cortex including the hippocampus. Similarly research over the past three decades has observed that such physical activity behaviors appear to enhance neural indices of attentional allocation and error monitoring which collectively facilitate behavioral interactions with the environment.

Beyond these system level influences, evidence also indicates that physical activity and the lack thereof has molecular and cellular influences on the brain. In both human and rodent models, physical activity has been observed to relate to increases in cerebral blood flow within regions of the brain supporting locomotion, the prefrontal cortex, and the hippocampus. Such increases in cerebral blood flow are brought about as a result of **angiogenesis** (i.e., the creation of new capillaries). Similarly, there is increased density of microglia and astrocytes within animal models following physical activity interventions.

One of the most consistently observed effects is that physical activity also appears to promote the creation and survival of new neurons (i.e., **neurogenesis**) which is thought to underlie enhanced learning and memory. Interestingly, these effects also appear to be heritable, with newborn rat pups exhibiting increased neuronal survival in the hippocampus if the mother was aerobically active during the gestational period of the pregnancy. Evidence from non-human animal models suggests that the sensitivity of cognitive processes and underlying brain structures to physical activity behaviors may occur as a result of human's evolutionary relationship with physical activity.

Adaptation — A feature or attribute refined through natural selection for its present role. Refers to a process by which the feature or attribute went through a period of selection for effectiveness to meet a particular need.

Strict Darwinism is a theory of evolutionary causation that grew in popularity during the 1940s and 1950s. Evolution occurs by natural selection acting upon individuals struggling for reproductive success. As success is measured in the transmission of genes to the next generation, anything that maximizes the passage of genes across generations will be favored. So a classic example is a species of butterfly that through adaptation acquires a pattern of coloring that resembles a dead leaf to reduce predation. But such a concept could similarly be applied in the context of fitting a small child's bike with side-supporting wheels to increase stability. Adaptation therefore encompasses changes in response to a clear need to enhance effective functioning.

While this is classically attributed at the individual level — an organism fighting for its own survival to pass on its distinct genetic profile; this concept also extends to relatives. Helping a relative who shares enough similar genes may do just as well as individual reproductive success for transmitting those genes to the next generation. The key characteristic is not that an individual organism evolves, but rather through successive generations the population refines a feature or attribute that fills a particular need.

The ideal scenario then is that within a species there will be a high level of variability of a feature or attribute across organisms. The high level of variability allows for a greater opportunity for an advantageous feature or attribute to emerge. However, while the feature or attribute will widely vary across organisms, the magnitude to which the features or attributes differ from previous generations will be small. The small extent of the difference from previous generations increases the likelihood that the advantageous feature or attribute survives long enough to pass on those genes. Through natural selection, the most successful feature or attribute will propagate into the next generation and be refined over multiple generations to support a particular function. Features or attributes that we share with other closely related species are most likely to reflect Adaptation. For instance, delayed hardening of skull bones is considered an adaptation to allow for larger heads as many mammalian ancestors and "lower" vertebrates share this feature with humans.

Evolutionary biology has preferentially focused on adaptations in part because it allows for clear causal explanations for the development of particular features or attributes within a species. The behavioral repertoire of an organism is examined within its environmental context (1), a reproductive advantage for a particular feature or attribute is posited (2), a genetic basis for that particular feature or attribute is investigated (3), and then inferences are made as to how natural selection may have led to its development (4). But how do we explain features or attributes that develop before there is a particular need for it? How did natural selection know to refine the features or attributes without first a clear need?

Exaptation — A feature or attribute that did not arise from an adaptation for its present role, but was subsequently coopted for its current function. Refers to an advantageous feature or attribute that occurred as a side-effect/byproduct of an adaptation to meet a different need. Features or attributes that are unique to a species are likely to reflect Exaptation.

Originally conceived of in the 1980s, the idea of **Exaptation** had largely fallen out of favor and its conceptual uniqueness had been subsumed within the broader framework of **Adaptation**. However, the very idea of using a feature or attribute for a purpose other than which it was designed or optimized for — or even using a feature or attribute that had no prior purpose — represents a fundamental divergence from the idea of Adaptation. Consider that with biological organisms, protowing feather structures existed long before the emergence of flight — with evidence suggesting they first existed as an adaptation for insulation and were only later coopted for flight. The field of computational biology and examinations of innovations in technology have led to a re-emergence of the idea of Exaptation. The technology behind your Microwave was not designed with the specific goal of more rapidly heating Ramen noodles. Rather the technology was designed for use in radar and was subsequently coopted as it exhibited a byproduct of rapidly causing water molecules to excite and generate heat.

Biologically, as we refine features or attributes through Adaptation we also introduce changes in underlying structures to support those features or attributes. In doing so, a range of cooptable potentials are made available as a side-effect or byproduct of these changes. Long-term evolutionary success relies upon leveraging quirky and underutilized potential to fill a need, much like an inventor using existing technology to create a new product. **Successful Exaptation nearly always leads to additional secondary Adaptation as features or attributes are refined for effectiveness to meet this new need/opportunity**.

The abilities of the human brain are thought to be the result of such an Exaptation. Anthropological evidence indicates that brain size did not begin to rapidly increase until after Gracile forms of Early Bipedal Hominids (Australopithecine) — the earliest examples of anatomically modern humans. Unlike Robust forms of Early Bipedal Hominids (Australopithecine) who exhibited pronounced sagittal crests of the skull and lived within wetter/more heavily forested regions; Gracile forms lived within more open regions that were less conducive to plant growth. The environment inhabited by Gracile forms required long-distance trekking and the adoption of endurance running to enhance survival.

Neurobiological adaptations to enhance aerobic capacity were achieved through the involvement of neurotrophins such as insulin-like growth factor 1 (IGF-1) which promoted the growth of longer limbs and muscle development, brain-derived neurotrophic factor (BDNF) which promoted more pronounced innervation of muscle fibers, and vascular endothelial growth factor (VEGF) which promoted greater vascularization of muscles. A side effect of these neurotrophins was that they began to also have impacts upon the brain: IGF-1 has potent effects on enhancing synaptic density, BDNF promotes enhanced creation and survival of new neurons (neurogenesis), and VEGF promotes enhanced development of blood vessels in the brain (angiogenesis). By altering signal systems involved with aerobic capacity, a byproduct occurred resulting in increases in brain size and cerebral vasculature. Anthropological evidence from near the end of the Gracile period indicates widespread cerebral vasculature not found in prior Early Bipedal Hominids. Even though Gracile forms had relatively small brain volume, adaptations to enhance aerobic capacity were coopted to enhance cognition and enabled future Adaptations in this area.

Collectively then, such evidence contributes to the perspective that human's evolutionary relationship with physical activity may have enabled our brains to develop our characteristically large prefrontal cortex and support high-level aspects of cognition. Adaptations to enhance aerobic capacity enabled exaptation for increased brain size and complexity. As a result, however, those same biological biases that enabled this development effectively require physical activity to support effective functioning of our neurobiology.

Additional Resources:

Diamond, A. (2012). Activities and programs that improve children's executive functions. Current Directions in Psychological Science, 21(5), 335–341. http://dx.doi.org/10.1177/0963721412453722

Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. Nature Reviews Neuroscience, 9(1), 58–65. http://dx.doi.org/10.1038/nrn2298

Gould, S. J. (1991). Exaptation: A crucial tool for an evolutionary psychology. Journal of Social Issues, 47, 3, 43–65. https://doi.org/10.1111/j.1540-4560.1991.tb01822.x

Raichlen, D. A., & Polk, J. D. (2013). Linking brains and brawn: Exercise and the evolution of human neurobiology. Proceedings of the Royal Society B: Biological Sciences, 280(1750), 20122250. http://dx.doi.org/10.1098/rspb.2012.2250

Research on the effect of exercise and physical activity behaviors on cognition began with a primary focus on trying to understand those factors that contribute towards elite sports performance.

Aim was to identify athletes with cognitive abilities that would enable then to become elite.

Aim was to use training programs to help athletes develop more 'elite-like' cognitive abilities.

Does training with a light-based system

provide any benefit?

Why do elite athletes exhibit faster reaction time and more rapid visual search processes that novice athletes and the general public?

Does training with a light-based system

provide any benefit?

Expert Performance approach

Studies the athlete under a sport-specific, or an ecologically valid, context.

- Across a wide variety of sports, in their sport-specific environmental contexts elite level athletes exhibit:
  - Superior decision-making
  - Superior spatial relational memory
  - Faster visual search

Does training with a light-based system

provide any benefit?

- Tries to understand why an athlete might exhibit superior performance in the sport specific context
  - Generally superior cognitive ability in a domain?
  - Specific to the athletes environment of expertise?
- Elite athletes in sport specific context may be able to rely on the habit system enabling fast and efficient responding.
- Novice athletes may have to rely upon the deliberative system.

Cognitive Component Skills approach

Studies the athletes abilities on core cognitive skills or abilities, free of sport specific context.

Does training with a light-based system

provide any benefit?

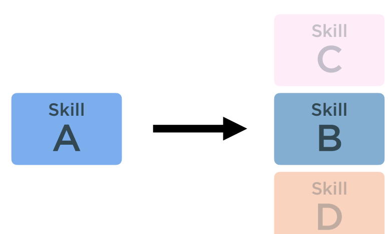
- Do elite athletes exhibit generally superior cognitive ability in a domain or is it specific to the athletes environment of expertise?
  - Elite athletes tend to have faster motor speed than novice athletes across a wide assortment of contexts.
  - Differences in visual search processes appear to be unique to sport-specific environmental information.
- Potential benefits should really only be applicable for motor speed since the light-based system has no sport-specific context.

Training

Transfer

Near (Narrow) Transfer

Learning and/or performance in one context has an influence on learning and/or performance on **highly similar movement** patterns or skills.

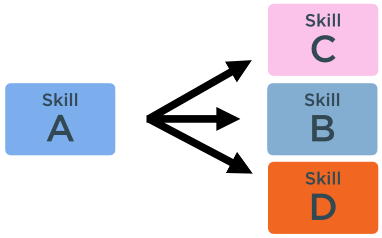


Training

Transfer

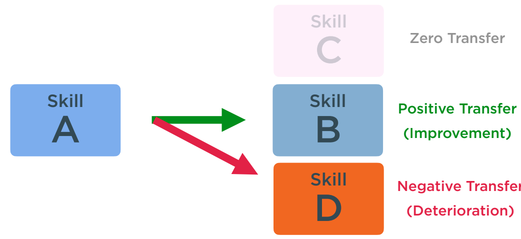
Far (Broad) Transfer

Learning and/or performance in one context has an influence on learning and/or performance **even for dissimilar movement** patterns or skills.



Training

Transfer



Does training with a light-based system

provide any benefit?

- What might be the transfer effect of light-based training to the sport-specific context?
  - Because it has Near Transfer, if the training closely mimics the sporting environment the training has been found to be effective.
    - Promoting rapid motor responses.
    - Promoting agility in movement speed.

Does training with a light-based system

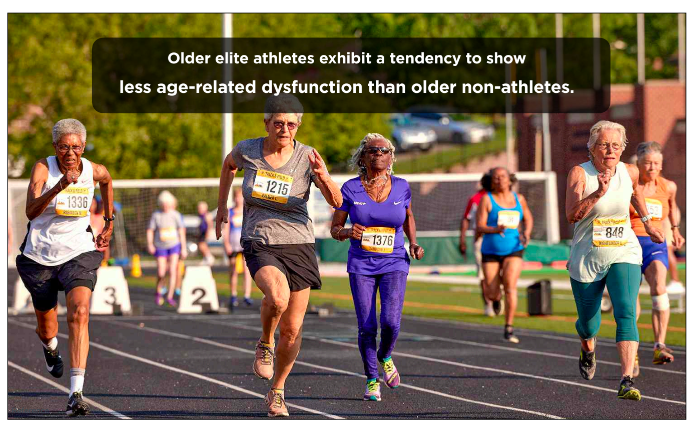
provide any benefit?

- What might be the transfer effect of light-based training to the sport-specific context?
  - Reflexive training with these devices has Zero Transfer outside of motor speed.
  - In sport-situations where an athlete must “read” an opponent, this training has been found to have Negative Transfer.
    - Training emphasizes respond quickly, the light-based cues are not contextually relevant to the sporting situation.

Does training with a light-based system

provide any benefit?

Although often promoted as “Cognitive”, “Neurocognitive”, or “Neuroscience-Based” training, there is little evidence for benefits beyond motor speed.



Chronic Physical Activity and
Cognition

Bottom Up Perspective

Activity should have the greatest effect for "low-level" cognitive processes (e.g., motor speed and information processing).

- Older elite athletes show less age-related dysfunction (faster motor speed and information processing).
  - Sporting environments emphasize and require more rapid decision making and action initiation.
  - Sport participation was assumed to train these skills.
- Dynamic Capacity suggests that those skills most often used will continue to improve.
  - These abilities are then better maintained with aging.

Chronic Physical Activity and
Cognition

Bottom Up Perspective

Activity should have the greatest effect for "low-level" cognitive processes (e.g., motor speed and information processing).

- "Low-level" cognitive processes (such as motor speed and information processing) should be alterable.
- "High-level" cognitive processes (such as cognitive control and relational memory) should be stable.

Chronic Physical Activity and
Cognition

- Large scale epidemiological investigations began to observe that:
  - Engagement in chronic physical activity behaviors was more relevant than current/former status as an athlete for cognition.

Chronic Physical Activity and
Cognition

- Chronic physical activity behaviors reduce the likelihood of developing mild cognitive impairment and dementia.
  - Engaging in higher levels of physical activity was associated with a 38% reduction in the risk of cognitive decline relative to those who are sedentary.
  - Engaging in low and moderate levels of physical activity was associated with a 35% reduction in the risk of cognitive decline.
  - Individuals who exhibited the lowest levels of physical activity based on accelerometery (e.g, those at or below the 10th percentile) were more than twice as likely to develop dementia as compared to those who engaged in more physical activity.

Chronic Physical Activity and
Cognition

- Initial research in this area observed that the relationship between chronic physical activity behaviors and cognition was:
  - Largest for older adults
  - Minimal relationships observed for middle aged adults (35 to 60)
  - No effects for young adult populations.

Chronic Physical Activity and
Cognition

- The assessment of cognition within epidemiological investigations tends to be rudimentary and has relied upon measures of global cognitive functioning or dementia screening tools.
  - Young adults even with poor cognitive abilities should still perform well on global cognitive functioning measures.
  - Most people should make very few errors on dementia screening tools.
  - Saturation & Ceiling effects

Chronic Physical Activity and

Cognition

- When the relationship between chronic physical activity behaviors and cognition is assessed using more appropriate and sensitive tools, engaging in physical activity has been associated with superior cognitive abilities across a wide range of cognitive domains (e.g., academic performance/achievement test scores, multiple domains of cognition, workplace performance) and age groups.
- Lower levels of physical activity before the age of 18 were the most predictive of development of cognitive impairment later in life.

Cerebellar Theory

- Bi-directional relationship between physical activity and the cerebellum.
  - Poor functioning of the cerebellum reduces the capacity to be physically active.
  - Physical activity positively influences neural plasticity in the cerebellum.
- Superior functioning of the cerebellum would allow more active individuals to exhibit faster motor speed and generally greater cognitive performance.
  - Most cognitive assessments rely upon the speed of a behavioral response to assess performance.

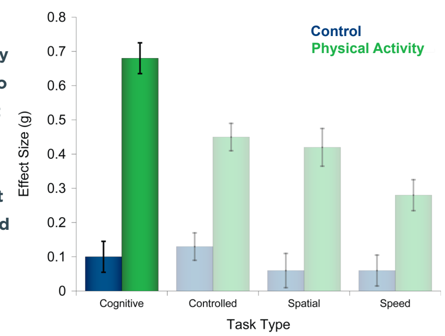
Superior cognitive function and lower incidence of age-related cognitive decline in those with greater chronic physical activity participation is the result of the beneficial effects of activity on the cerebellum.

Cerebellar Theory

- The cerebellum also supports other aspects of cognition by coordinating and preparing neural responses.
  - Would also explain improved function of aspects of attention and information processing; resulting in lower incidence of age-related cognitive decline.

Superior cognitive function and lower incidence of age-related cognitive decline in those with greater chronic physical activity participation is the result of the beneficial effects of activity on the cerebellum.

Chronic physical activity participation appears to exert a general benefit across all aspects of cognition, but that effect appears greatest for cognitive control and relational memory.



Chronic Physical Activity and

Cognition

Top Down Perspective

Idea that high-level cognitive and memory operations should be the most reactive to systemic changes to protect the integrity of the organism.

- The very nature of “high-level” cognitive processes make it essential that they are reactive to changes in bodily functioning.
  - They are dynamic every changing systems that regulate our functioning.
  - They are energetically demanding.
    - If energetic needs are not met, diminished functioning should be expected.
  - “Low-level” cognitive processes are the least energetically demanding.

Empirical evidence supports that high school athletes (as a group) receive better grades than nonathletes, and have higher academic aspirations.

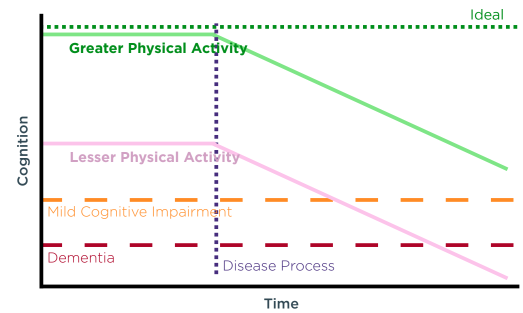
Sport Participation and

Academic Performance

Empirical evidence supports that high school athletes (as a group) receive better grades than nonathletes, and have higher academic aspirations.

- Sympathetic teachers awarding higher grades to athletes to keep them athletically eligible.
- Physical activity may support and promote the development of greater cognitive abilities.
- Generally attributed to two prominent factors:
  - Athletic participation builds discipline, strong work ethic, and teaches achievement orientation. These qualities can be applied to academics.
  - Athletes may have higher GPAs due to the fact that they must meet minimum standards to be eligible to play.

Reserve Theory



Nature of the Relationship

Much of the epidemiological research is cross sectional observations between a behavior (e.g., physical activity) and an outcome (e.g., cognition).

Physical Activity → Cognition

Behavioral Causality

Engaging in habitual physical activity results in improved cognition.

We should get people to be more active to enhance their cognitive abilities.

Cognition → Physical Activity

Reverse Causality

Individuals with superior cognition are better able to sustain habitual physical activity patterns.

We should enhance cognitive abilities to help people engage in healthier lifestyles.

Chronic Physical Activity and

Cognition

There is a bi-directional relationship between high-level cognitive abilities and chronic physical activity behaviors.

- Engaging in physical activity interventions (approaches designed specifically to increase physical activity behaviors) promotes:
  - A general facilitation in cognitive performance
  - A selectively larger benefit for aspects of cognitive control and declarative (relational) memory.
- The vast majority of this research has contrasted the potential benefits of aerobic exercise training against non-aerobic stretching and toning training.

Chronic Physical Activity and

Cognition

- The brain requires energetic resources to effectively function.
- An individual with superior cardiovascular fitness exhibits a greater ability to efficiently generate and utilize metabolic resources.
  - Can allocate more energetic resources towards cognitive processes
  - Can sustain energetically demanding cognitive processes (e.g., high-level cognitive operations) to a greater extent

Cardiovascular Fitness Hypothesis

Superior cognitive function in those with greater chronic physical activity participation is the result of greater cardiovascular fitness.

Chronic Physical Activity and

Cognition

- Evidence from cross sectional studies has consistently revealed a strong relationship across the lifespan such that greater cardiovascular fitness relates to superior function of cognitive control and declarative memory processes.
- Aerobic exercise interventions also appear to positively attenuate (reduce) age-related decline in cognition and promote enhancements in cognitive control and declarative memory.

Cardiovascular Fitness Hypothesis

Superior cognitive function in those with greater chronic physical activity participation is the result of greater cardiovascular fitness.

Chronic Physical Activity and

Cognition

- A consistent finding is that these beneficial effects are unrelated to the extent to which the intervention was able to induce changes in cardiovascular fitness.
- The evidence indicates that while aerobic exercise is beneficial, it is not necessary to incur cardiovascular adaptations to observe a benefit for cognition — regardless of how energetically demanding the aspect of cognition.

Cardiovascular Fitness Hypothesis

Superior cognitive function in those with greater chronic physical activity participation is the result of greater cardiovascular fitness.

Chronic Physical Activity and

Cognition

- However, relatively minimal changes in cardiovascular fitness can be achieved over the course of a typical 8 to 12 month intervention period.
  - Cross-sectional studies compare large-scale differences in fitness (<30th percentile vs >70th percentile).
  - Over an 8 month period, an individual at the 3rd percentile might only improve fitness to the 10th percentile.
- It may be that the lack of a relationship with cardiovascular fitness is due to floor effects in the change in fitness measures.

Cardiovascular Fitness Hypothesis

Superior cognitive function in those with greater chronic physical activity participation is the result of greater cardiovascular fitness.

Chronic Physical Activity and

Cognition

Cognitive Training Hypothesis

Superior cognitive function in those with greater chronic physical activity participation is the result of physical activity serving as a form of cognitive training.

- Conceptually similar to the context of reverse causality.
- Sustaining habitual physical activity patterns requires considerable “high-level” cognitive abilities.
  - Planning, goal setting, and suppressing dominant tendencies (i.e., discipline) in order to maintain behaviors oriented towards their goal.
  - Acquire and maintain new information about movement patterns, spatial relationships, environmental awareness, and previous behaviors.

Chronic Physical Activity and

Cognition

Cognitive Training Hypothesis

Superior cognitive function in those with greater chronic physical activity participation is the result of physical activity serving as a form of cognitive training.

- Suggests that the very nature of working to become more physically active acts as a form of cognitive training.
- Although cognitive training typically exhibits near transfer; in this case, the training fundamentally aligns with the aspect of cognition so it should provide a benefit to those cognitive domains more broadly.
  - Abilities that are used are enhanced.

Chronic Physical Activity and

Cognition

Cognitive Training Hypothesis

Superior cognitive function in those with greater chronic physical activity participation is the result of physical activity serving as a form of cognitive training.

- Engaging in aerobic exercise training might provide greater cognitive benefits than stretching/toning exercises simply because it is more effortful to sustain those behavioral patterns — requiring greater “high-level” cognitive processes to maintain.
- A key characteristic of cognitive training is that it only works if it pushes the individual to the limits of their cognitive ability.

Physical Activity as

Cognitive Training

Aerobic exercises implemented in contexts where the individual:

- Has little autonomy over sustaining the behavior.
- Has little need to remember what to do and when to do it.
- In an environment that requires no relational memory to recall where the individual is or needs to go.

Likely to have minimal benefit for improving cognition

Physical Activity as

Cognitive Training

Activities which require considerable engagement of cognitive control and declarative memory would be expected to show superior benefits.

- Health promotion efforts oriented towards supporting cognition and avoiding age-related cognitive decline would benefit from shifting away from the aerobic exercise emphasis and instead emphasize activities such as dance, martial arts, and novel (new) games/activities.
- Activities that increase perceptions of joy, feelings of social support and belonging, and build confidence have been observed to positively benefit both cognitive control and declarative memory.

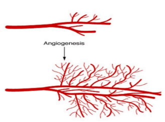
Physical activity has been observed to relate to increases in cerebral blood flow within regions of the brain supporting locomotion, the prefrontal cortex, and the hippocampus

Physical Activity and Cognition

Neural Mechanisms

Angiogenesis

The growth of new blood vessels.



- Angiogenesis is believed to underlie increases in cerebral blood flow in response to physical activity.
- Following chronic physical activity there is also an increased density of microglia and astrocytes which work to alter blood flow within the brain.

Physical Activity and Cognition

Neural Mechanisms

Neurogenesis

The creation and survival of new neurons.

- One of the most consistently observed effects is that physical activity also appears to promote the creation and survival of new neurons which is thought to underlie enhanced learning and memory.
- These effects also appear to be heritable, with newborn rat pups exhibiting increased neuronal survival in the hippocampus if the mother was aerobically active during the gestational period of the pregnancy.

Adaptation

A feature or attribute refined through natural selection for its present role. Refers to a process by which the feature or attribute went through a period of selection for effectiveness to meet a particular need.

Adaptation encompasses changes in response to a clear need to enhance effective functioning.

- Fundamental principle advocated by Strict Darwinism regarding evolutionary causation that grew in popularity during the 1940s and 1950s.
- Evolution occurs by natural selection acting upon individuals struggling for reproductive success.
  - As success is measured in the transmission of genes to the next generation, anything that maximizes the passage of genes across generations will be favored.
  - Helping a relative who shares enough similar genes may do just as well as individual reproductive success for transmitting those genes to the next generation.
  - The key characteristic is not that an individual organism evolves, but rather through successive generations the population refines a feature or attribute that fills a particular need.

Adaptation

A feature or attribute refined through natural selection for its present role. Refers to a process by which the feature or attribute went through a period of selection for effectiveness to meet a particular need.

Adaptation encompasses changes in response to a clear need to enhance effective functioning.

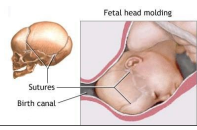
- The ideal scenario is that within a species there will be a high level of variability of a feature or attribute across organisms.
  - The high level of variability allows for a greater opportunity for an advantageous feature or attribute to emerge.
- While the feature or attribute will widely vary across organisms, the magnitude to which the features or attributes differ from previous generations will be small.
  - The small extent of the difference from previous generations increases the likelihood that the advantageous feature or attribute survives long enough to pass on those genes.

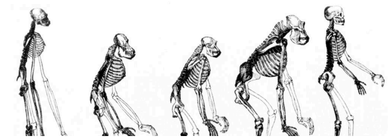
Adaptation

A feature or attribute refined through natural selection for its present role. Refers to a process by which the feature or attribute went through a period of selection for effectiveness to meet a particular need.

Adaptation encompasses changes in response to a clear need to enhance effective functioning.

- Through natural selection, the most successful feature or attribute will propagate into the next generation and be refined over multiple generations to support a particular function.
- Features or attributes that we share with other closely related species are most likely to reflect Adaptation.
  - Delayed hardening of skull bones is considered an adaptation to allow for larger heads as many mammalian ancestors and "lower" vertebrates share this feature with humans.





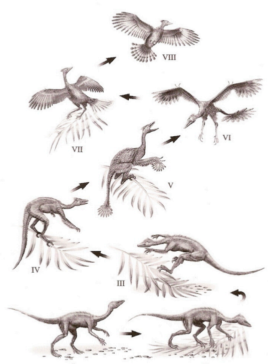
Evolutionary biology has preferentially focused on adaptations in part because it allows for clear causal explanations for the development of particular features or attributes within a species.

- The behavioral repertoire of an organism is examined within its environmental context.
- A reproductive advantage for a particular feature or attribute is posited.
- A genetic basis for that particular feature or attribute is investigated.
- Then inferences are made as to how natural selection may have led to its development.

Exaptation

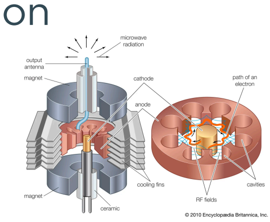
A feature or attribute that did not arise from an adaptation for its present role, but was subsequently coopted for its current function.
Refers to an advantageous feature or attribute that occurred as a side-effect/byproduct of an adaptation to meet a different need.

Features or attributes that are unique to a species are likely to reflect Exaptation.



Exaptation

- Originally conceived of in the 1980s, the idea of Exaptation had largely fallen out of favor and its conceptual uniqueness had been subsumed within the broader framework of Adaptation.
- The very idea of using a feature or attribute for a purpose other than which it was designed or optimized for — or even using a feature or attribute that had no prior purpose — represents a fundamental divergence from the idea of Adaptation.
- The field of computational biology and examinations of innovations in technology have led to a re-emergence of the idea of Exaptation.



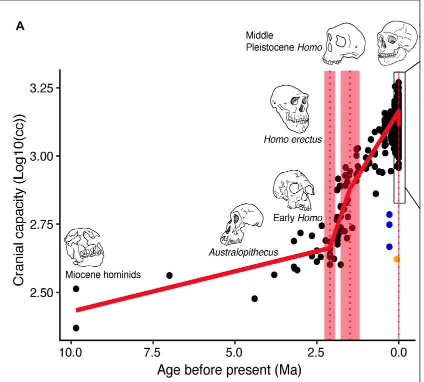
Exaptation

- Biologically, as we refine features or attributes through Adaptation we also introduce changes in underlying structures to support those features or attributes.
- In doing so, a range of cooptable potentials are made available as a side-effect or byproduct of these changes.
- Long-term evolutionary success relies upon leveraging quirky and underutilized potential to fill a need, much like an inventor using existing technology to create a new product.

Exaptations reflect unintended features/benefits made possible by adaptations (which occurred for other reasons).

Successful Exaptation nearly always leads to additional secondary Adaptation as features or attributes are refined for effectiveness to meet this new need/ opportunity.

Increases in cranial capacity
(which generally serves as an analog of potential brain size)
showed a rapid change following the emergence of Gracile forms of Early Bipedal Hominids.

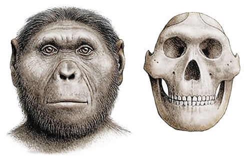


Robust forms
of Early Bipedal Hominids

Exhibited pronounced “gorilla-like” sagittal crests of the skull.

Lived in wetter/more heavily forested regions.

Cranial capacity similar to a chimpanzee.



Gracile forms
of Early Bipedal Hominids

Earliest example of anatomically modern humans.

Lived in open savanna landscapes less conducive to plant growth.

Presence of widespread cerebral vasculature.

Natural selection to environments which required long-distance trekking and the adoption of endurance running would have resulted in adaptations for aerobic fitness

- **Insulin-like Growth Factor 1 (IGF-1)**

  Promoting the growth of longer limbs and muscle development.

- **Brain-Derived Neurotrophic Factor (BDNF)**

  Promoting more pronounced innervation of muscle fibers.

- **Vascular Endothelial Growth Factor (VEGF)**

  Greater vascularization of muscles.

Exaptation
(side effects of adaptation)
of the increased concentration of these neurotrophins resulted in increases in brain size and cerebral vasculature.

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- **Insulin-like Growth Factor 1 (IGF-1)**

  Promoting the growth of longer limbs and muscle development.
  Also increases synaptic density of neurons.

- **Brain-Derived Neurotrophic Factor (BDNF)**

  Promoting more pronounced innervation of muscle fibers.
  Also promotes enhanced creation and survival of new neurons.

- **Vascular Endothelial Growth Factor (VEGF)**

  Greater vascularization of muscles.
  Also promotes the development of blood vessels in the brain.

Increases in cranial capacity
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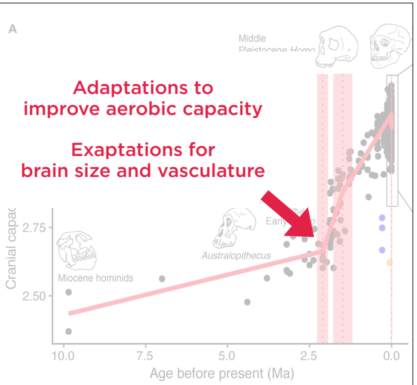

Physical Activity and Cognition
Neural Mechanisms

Biological Need

Physical activity may be a requirement to support effective functioning of our neurobiology as a byproduct of the evolutionary need to enhance aerobic fitness.

- Gracile forms of Early Bipedal Hominids had small brain volume.
  - Adaptations for aerobic fitness lead to Exaptation of brain growth and vasculature.
  - Secondary adaptation promoted further refinement of this to increase brain size and capabilities.
    - Large prefrontal cortex
    - High level aspects of cognition