5 | Ecology of the mind and adaptive learning

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ABSTRACT

This chapter explores how adaptive expertise in engineering education can be cultivated through ecological and embodied learning approaches. Drawing on theories from ecological psychology, embodied cognition, and ecological dynamics, we argue that expertise is not solely a cognitive trait but emerges from continuous interaction between learners, their bodies, tasks, and environments. Using the recurring case of Jenny – a biomedical engineering student developing a device for coronary thrombus treatment – the chapter illustrates how adaptive expertise involves perception-action loops, motor skill acquisition, and contextual responsiveness. Central to the argument is the concept of ecology of mind, which frames cognition as a relational process shaped by environmental affordances and bodily experiences. The chapter challenges traditional views of motor learning as repetitive practice, instead emphasizing variability and exploration as key to developing flexible, innovative problem-solving skills. It introduces pedagogical strategies such as the PoST framework and supervision models that balance closure and discovery, supporting learners in navigating complex, real-world challenges.

By integrating ecological and embodied perspectives, we propose a holistic view of learning where cognition is enacted through doing, sensing, and adapting. This approach prepares engineering students not just to perform routine tasks but to innovate responsibly in dynamic environments. Ultimately, the chapter offers practical guidelines for educators to design learning environments that foster adaptive expertise through contextual richness, variability, and reflective supervision.

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JENNY'S CASE *Jenny is a final-year biomedical engineering student who has been tasked by her thesis supervisor to come up with an innovative way of administering treatment for coronary thrombus. The solution should be less invasive than conventional solutions and should also be cost-effective. As a part of this, she will need to develop and test her solution in a simulated setting. In this context, she will be assessing the manoeuvrability of her innovation.*
To do this, motor skills are crucial for the precise manipulation of tools and instruments during the design and prototyping phases. As her solution involves a device that requires precise manipulation within the human body, a high level of fine motor control to navigate through delicate tissues and perform intricate procedures is needed. This requires her to creatively apply and adapt solutions and innovate on current ways of administering this treatment. However, this also requires a deep understanding of how the end user will apply her solution. [1]

1 To visually distinguish this case example and highlight its relevance throughout the chapter, we have styled this scenario as a recurring case study under the name 'Jenny's Case,' which will be referenced in several sections to illustrate key concepts.

Introduction

Rather than simply memorising a great deal of information by heart, engineering education serves to teach good problem-solving skills based on a deep understanding of key concepts in engineering (Litzinger et al., 2011). Novel learners in engineering should therefore move from making surface-level connections between principles to developing more in-depth knowledge around the underlying concepts that connect these principles (Litzinger et al., 2011).

Thus, instead of teaching for knowledge through rote learning, teachers should strive to foster the development of "mental models" for key concepts within their field (Hatano, 1982; Hatano & Inagaki, 1986). Mental models help learners simulate problem-solving scenarios in their minds, enabling them to predict outcomes and adapt existing knowledge to new contexts.

A mental model should be understood as a comprehension of how something works or as an internal representation of external reality, i.e. a way of representing reality within one's mind which allows for mental simulation of how the procedure works. This allows one to make predictions or explanations about unfamiliar situations and helps when creating solutions to novel problems (Hatano & Inagaki, 1986).

This is where the concept of adaptive expertise becomes relevant. Adaptive expertise describes the ability to transfer and flexibly apply mental models to novel and complex problems. It offers a lens for understanding how engineers can go beyond routine practice and innovate in unfamiliar situations.

While adaptive expertise is widely recognised as a conceptual framework for understanding expert performance (Carbonell et al., 2014; Pelgrim et al., 2022), much of the foundational and developmental literature has focused on the trajectory towards becoming an adaptive expert, often emphasising growth pathways. An example is the "optimal adaptability corridor" (Bransford & Schwartz, 1999; Schwartz et al., 2005), which conceptualises adaptability as a cultivated process en route to expertise. However, in ecological psychology, behaviour is seen as an interaction between the individual and the context, and when adaptive expertise is seen from this perspective, recent research shows that even novices can employ adaptive cognitive practices (Gamborg et al., 2024). This indicates that adaptive behaviours are fairly generic competencies that we can foster early in training. This research also points to a high degree of contextuality in the ability to engage in these cognitive adaptive practices (Gamborg et al., 2023).

Historically, the exploration of adaptive expertise has focused almost exclusively on cognitive skills in isolation, largely overlooking the critical role of contextual and bodily factors in shaping expert performance. However, adaptive expertise also manifests in how individuals physically engage with their environments, for example through motor control. This in spite of the fact that research proposes that all skilled motor movement reflects components of adaptive expertise (Jensen et al., 2022).

A motor skill is a function that involves specific movements of the body's muscles to perform a task (Moini et al., 2024). Research shows that repetitive motor control is less repetitive than what is often perceived and emphasises how the inherent variability of the neuromuscular system may be leveraged to design training that promotes adaptive expertise when learning to perform motor skills (Jensen et al., 2022).

To bridge this gap, the present chapter introduces ecological cognition, grounded in the theory of perception proposed by Gibson. This perspective emphasises that expertise is not only cognitive but also embodied, arising from the continuous interaction between the learners and their environment. Cognition, from this view, is not just "in the head of the individual" but is shaped through sensorimotor engagement with the world.

JENNY'S CASE ***Ecological cognition***

In Jenny's case, her understanding of how the wire moves through simulated tissue develops not just through mental planning, but also by physically interacting with different prototypes and adjusting her movements based on feedback from the environment. These affordances guide her perception of what actions are possible.

This chapter will discuss how cognition is a function of bodily experiences. It links motor learning and adaptive expertise by arguing that adaptivity relies on affordances of the environment and that the division between cognition and motor skills seems arbitrary from this perspective.

Gibson and the theory of ecology of mind

To better understand how context and perception shape adaptive expertise, this section introduces ecological cognition – a theoretical lens that emphasises the reciprocal relationship between individuals and their environments. We begin by outlining key contributors to this perspective, including Bateson and Gibson. The term "ecological cognition" refers to how people's social and environmental context is deeply intertwined with the development of their ideas, which, in turn, influence that same context and their experiences (Bateson, 1991).

Bateson's work represents a shift in cognitive theory towards recognising the importance of context and social interaction. He argued that cognition is not a detached, internal activity, but a naturalistic phenomenon embedded within the broader ecosystem of human behaviour and interactions. A similar line of thought is found in Gibson's ecological psychology, which emphasises how perception is a direct, action-oriented engagement with the environment (Gibson, 1979). Sekuler and Blake (2002, p.621) describe perception as the "The acquisition and processing of sensory information in order to see, hear, taste, or feel objects in the world…". Here, Gibson emphasised the importance of feedback from the perceptual field in order to move throughout our environment (Gibson, 1979). In this sense, Gibson argued for an ecological take on cognitive activity, which proposes that cognition, as a psychological endeavour, is impacted by environment, social actors, and culture, and these factors are inherently connected when we learn (Gibson, 1979; Gibson & Gibson, 1955).

Important to note here is that ecological psychology arose in the face of behaviouristic psychology which viewed psychological activities as reactions (behaviours) to external stimuli. Ecological psychology emerged as a competing thinking, positing that cognition emerges from an organism's embeddedness in its environment, viewing psychological phenomena as arising in, and moderated by the "ecology" of human existence, i.e. shaped by evolutionary, perceptual, and contextual factors. To Gibson, this ecology was a consequence of evolutionary developments in perception that allowed humans to interact with their environment by "resonating" with outside entities rather than being direct reactions to stimuli (Gibson, 1986).

Perceptual learning was thereby characterised by changes in what was perceived. This could happen either through processes of enriching existing cognitive sensory perception with something "new", or by progressively hone an ill-constructed percept into a more refined perception, that allowed for more accurate perception of the stimuli (Gibson & Gibson, 1955). In this view, perception becomes a skill: the learner "picks up" relevant environmental cues and adapts their actions accordingly.

Unlike traditional cognitive theories, ecological perspectives do not see perception as internal computation but as a relational process between organism and environment. This view implies that the environment is filled with objects that provide opportunities for cognitive events to happen. Therefore, from an ecological perspective on cognition, an individual's cognitive activities are intricately connected with their surrounding environment where interactions with objects stimulate and support cognitive processes.

For example, problem-solving does not occur in isolation, it is informed by environmental cues, tools, and prior experiences. People do not produce a solution solely based on their rational capabilities. Instead, it happens as a function of their prior experience, leading them to imagine viable solutions and interacting with their environment for inspiration on how to adapt these experiences to the problem. Moments of insight – so-called "Aha moments" – will come as a function of prior experiences in which case current perceptions interact with past embodied experiences, allowing individuals to bridge those experiences to prompt sudden realisation of a solution to a current problem. Or experiences that are happening in-the-moment will prompt solutions to prior or lingering problems.

JENNY'S CASE ***Exploration of affordances that support adaptation***
Looking at the case in the beginning of this chapter, Jenny will use her conceptual understanding of manoeuvring a wire in areas with soft and delicate tissue when she is exploring different possibilities to access the coronary thrombosis. During this exploration, her perception of the environment will shape her actions in an adaptive manner, and her previous experiences with manoeuvring wires will help her adjust the solution to the problem at hand.

However, an important aspect of this approach to cognition is to reiterate the premise that cognitive activity is still the virtue of the individual. As Gibson argues: "Perception is an achievement of the individual, not an appearance in the theater of his consciousness" (Gibson, 1979, p. 239). While Gibson argued that perception, when seen as information pickup, does not require memory, the process of making meaning of this information pick-up does (Gibson, 1986). Here, his theory of affordances comes into place, which he defines as "...properties taken with reference to the observer." (Gibson, 1986, p.143).

Take the sensory experience of touching grass. We all know how it feels and this "knowing" provides us with idiosyncratic desires for interacting with the grass – do we like to feel it? What are our previous experiences of the properties of grass - as having visual, haptic, and practical values? Those experiences are what dictate the affordances of objects – how we perceive the object, how we engage with it, what it proposes that we can do with the object to serve our human experience.

Taken further, Gibson argued that the only relevant information there is to perceive is what we "pick up" about an object; how we make meaning of it and how we can interact with it, i.e. its affordances. Therefore, the accuracy of our perception becomes more refined with experience: "The information that is picked up... becomes more and more subtle, elaborate, and precise with practice. One can keep on learning to perceive as long as life goes on..." (Gibson, 1979, p.245).

Thus, affordances are a central component when engaging with epistemic distancing, where the learners are assessing the applicability of their current knowledge to a novel problem-solving task. Understanding perceptual activities is therefore inherent to understanding adaptive expertise, or, adaptive expert behaviours (Gamborg et al., 2024). According to Leont'ev, learning is rooted in an "orientation reflex", where the organism, through its bodily signals, commands motor behaviour as a response to the environment. These commands are then compared to inputs about the results of the actions made, and discrepancies are the object for regulating behaviour. Thereby, learning from one's experiences is both a physiological and psychological enterprise. Learning arises when input is different from the anticipated result (Leont'ev, 1978).

In the same way, adaptive expert behaviours are catalysed when we engage with something novel to us (Mylopoulos & Regehr, 2009). In this sense, learning is a situated practice that relies on ecological, sociocultural, and embodied cognitive processes, which help develop mental models of concepts. Through perceptual affordances, it creates opportunities for learners to devise innovative solutions to new problems.

In this way, cognition is a continual process of perceiving and reacting to affordances, and adaptive behaviour arises when discrepancies surface between the actual outcomes and the expected outcomes that are dictated by our previous physiological and psychological experiences. Therefore, context is paramount to the elicitation of adaptive expert behaviour, just as much as individual cognitive competence and knowledge are.

Ecology of mind and its relation to embodied cognition

To deepen our understanding of ecological cognition, we now explore how it connects to the theory of embodied cognition. This perspective highlights how our thinking is shaped by our bodily experiences: what we see, feel, and do. In his work on grounded cognition, Barsalou (2008), explains that when we think, we often mentally "replay" past experiences. These mental simulations draw on the same systems in the brain as were active during the original perception or action. In other words, our ability to think, remember, and solve problems is closely tied to how we have physically interacted with the world.

According to the theory of embodied cognition, the body impacts cognitive activities, in that, sensory experiences shape cognition. Bodily sensoria are not constraining cognitive activities, but the enactment of them (Foglia & Wilson, 2013). Importantly, knowledge structures exist and can function without sensory experiences, but bodily experiences may prompt recall of specific memories, which, in turn, can impact how one acts on knowledge (Foglia & Wilson, 2013). Thus, embodied cognition explains how adaptive practices may be shaped by sensory experience.

Embodied cognitive activities serve a functional purpose: they are directed towards solving tasks, which, in turn, are steps in broader problem-solving processes (Wilson & Golonka, 2013). This can be both helpful and impeding. On one hand, having sensory experiences can prompt cognitive activities that help innovative problem solving by retrieving conceptual knowledge from other "mental models" and innovatively applying them to the problem at hand. However, it may also constrict problem solving to routine knowledge if this sensory input is prompting a well-known solution, which may not be appropriate to the problem at hand.

JENNY'S CASE ***Innovative insights through embodied discovery***
Jenny is watering her plants in the garden when suddenly noticing how water flows through the hose. This observation reminds her of the vascular system and sparks an idea for how to design her device to flow more smoothly through coronary arteries. Alternatively, she might glance at an old award she received for a thrombus device and reflexively try to apply that solution to her current challenge, before realising, through experimentation, that the same solution may not fit into the new anatomical and functional context.

By aligning embodied cognition with ecological cognition as posed by the theories of Gibson and Leont'ev, we highlight the interconnectedness of cognition, environment, and action. In this sense, an ecological approach to adaptive expertise adopts a more radical approach to embodied cognition, emphasizing that cognitive processes are not only influenced by bodily experiences but are co-shaped by all interactions with objects, artifacts, and other humans and animals.

JENNY'S CASE ***Innovative insights through embodied discovery***
For Jenny, each iteration with different prototypes or tool dimensions not only reshapes her hand movements but also reconfigures her understanding of how her solution will function in a clinical setting. Her learning is grounded in this continuous body-environment interaction. Every element within the environment becomes a contributor to how her thinking unfolds. For example, when Jenny experiences the flow of water while gardening, this interaction not only prompts her cognitive reflection but also informs her understanding of vascular dynamics. Her cognition emerges from this rich tapestry of interactions rather than from isolated mental representations or internalised knowledge alone.

By framing embodied cognition through the lens of adaptive expertise, it is crucial for teachers to teach learners to recognise how their environment, including tools and other human beings, influences their cognitive activities. This understanding fosters an awareness of when to rely on established routines and when to innovate.

JENNY'S CASE ***Innovative insights through embodied discovery***
The case of Jenny illustrates this well: while she may draw upon past knowledge, her interaction with her environment can lead to novel insights and solutions.

This radical perspective on embodied cognition encourages a holistic view of learning and problem-solving, where all elements of the environment are considered integral to cognitive development. Integrating these ideas into engineering education may help teachers to prepare learners to navigate complex challenges with adaptability and creativity, effectively co-creating solutions in response to their dynamic environments. By viewing adaptive expertise through ecological psychology, this chapter argues that engineering education should aim to prepare learners like Jenny to be adaptable and to engage in innovation rather than just applying a routine solution. A way of learning this is by approaching adaptive expertise as an ecology of mind, which we will explain in the next section.

Adaptive expertise as an ecology of mind

Historically, research on expertise has often emphasised how knowledge acquisition and intentional, repeated practice are the foundation for developing expert performance (Ericsson, 2004, 2015; Ericsson & Charness, 1994). Other perspectives highlight that expertise is also shaped by the specific content and context in which learning occurs, focusing on how learners build expert knowledge through experience in real-world settings (Elstein & Schwarz, 2002; Norman, 2000). In contrast to these views, this chapter argued that adaptive expertise is grounded in the dynamic interaction between cognition and context. This view expands traditional perspectives by emphasising cognitive flexibility that is applicable across domains, and highlighting the social dimensions of learning and adaptation (Moulton et al., 2007; Mylopoulos & Farhat, 2015).

The concept of adaptive expertise is strongly linked to that of distributed cognition, which proposes that cognitive activities are embedded in a social, cultural, and physical world (Hutchins, 1995). The distributed quality of cognitive activities refers to what in cultural-historical activity theory (Lave, 1988; Leont'ev, 1978) is described as a natural – or ecological – dialectic interaction between these cognitive activities and context (Hutchins, 2010). From this standpoint, adaptive expertise emerges not only from individual mental capacities but also from the interaction with social practices, tools, and environmental affordances (Gibson, 1986; Hutchins, 1995). Jenny's insights are not developed in isolation but through ongoing feedback from supervisors, her tools, and the simulated patient environment. These external factors help co-construct the design decisions she makes.

Similarly, such social aspects of learning in engineering have been described by Deters et al. (2024) as a third layer of also "knowing with", focusing on how engineers can transfer learning to other contexts by integrating and adapting experiences into new solutions. Here, learning is propelled by social exchange in collaborative learning environments, where adaptability is the sum of co-created solutions to novel problems.

Ultimately, this perspective highlights that the ability to apply knowledge adaptively is not only an individual skill, but a socially mediated competence shaped by real-time interactions with others, tools, and settings.

Adaptive expertise and motor learning in engineering

Building on the previous sections which emphasised how cognition emerges through interaction with our environment, we now turn to the role of motor learning as a key component of adaptive expertise. Motor skills not only reflect the integration of perception and action but also highlight how adaptability is enacted physically through engagement with tools, environments, and tasks.

Although motor skills are often underemphasised in engineering education, they play a crucial role in many areas of engineering practice. An example is the need for hand-eye coordination and spatial awareness when developing biomedical solutions for surgical procedures, as demonstrated in Jenny's case. In such situations, the engineer may be required to perform tasks such as implantation or other medical procedures as a step in the development or implementation of their engineered solutions. This requires the ability to foreshadow affordances of such technical equipment for surgeons, which may require engineers to acquire such motor skills. Therefore, it would be reasonable to talk about the acquisition of motor skills during biomedical engineering education.

Motor skill acquisition, also referred to as motor learning and control, is the interdisciplinary science of intention, perception, action, and calibration of the learner-environment relationship. In particular, skill acquisition is an umbrella term specific to the knowledge about which behavioural and neurological variables influence central nervous system adaptation in response to the learning of a motor skill (Magill & Anderson, 2010).

However, to make recommendations for how to implement skill acquisition in engineering education, it is imperative that we are aware of what exactly is acquired in motor skill acquisition.

JENNY'S CASE ***Motor skill acquisition***

In Jenny's case, acquisition of motor skills refers not only to mastering the manipulation of the wire but also developing a sensitivity as to how her hands respond to subtle resistance and tactile cues during practice. Her learning is not about perfect repetition, but about flexible adaptation.

This is supported by research proposing that all skilled motor movement reflects components of adaptive expertise (Jensen et al., 2022), but these movements are not simply repetitive drills. Rather, the neuro-muscular system's inherent variability can be harnessed to design training environments that foster adaptability. Repetitive motor practice, when viewed through this lens, is much less repetitive than it may appear: each iteration involves subtle adjustments and learning opportunities (Jensen et al., 2022).

Araújo and Davids (2011) emphasise that skill acquisition is primarily a process of adapting to specific performance environments. Through this adaptation, learners establish connections between perceptual information and movement – what they call functional information-movement couplings

– which are foundational to motor expertise (Araújo & Davids, 2011; Davids et al., 2012). In this view, learners are seen as adaptive systems whose behaviours emerge in response to constraints presented by tasks and environments, aligning with Gibson's ecological theory of perception (Gibson, 1979). Hence, the functional movement performed by learners in engineering during motor learning sessions is underpinned by their perceptions, intentions, and actions, which are seen as intertwined. Therefore, learning environments should allow learners to use movement variability to explore and create opportunities for action. Rather than prescribing fixed procedures, educators should enable learners to explore different motor strategies, supporting the emergence of adaptive responses (Davids et al., 2013). This emphasis on variability and interaction builds directly on the ecological and embodied frameworks discussed earlier in this chapter.

Ecological dynamics in skill acquisition and the importance of variability

To further unpack how variability supports adaptive expertise, we now turn to ecological dynamics – a framework that integrates ecological psychology with dynamical systems theory to explain how motor skills emerge in real-world settings. This perspective helps clarify how learners adapt to changing conditions by interacting with task constraints, environmental cues, and their own bodily capacities.

It builds directly on the idea that motor learning is not about repeating ideal forms but about attuning to context through perception-action couplings. Here, variability is a cornerstone in the adaptive expert framework, as Hatano writes: "...in order to acquire conceptual knowledge, it is necessary to examine systematically the effects of variations in the procedure upon the outcome." (Hatano, 1982, p.16).
Just as variability in cognitive functioning is crucial for developing adaptive expert behaviours, it is equally important in motor functioning, and thus in the way the mind and body collaborate in learning environments. Bernstein's (1967) famous statement "Repetition without repetition", highlights that no two movement patterns will ever be the same.

Therefore, it is imperative not to engage in rote, repetitive practice when leaning a new motor skill that should be applied in a dynamic and complex environment. To solve a motor problem consistently under a variety of conditions, the learner must experience as many modifications of the task as possible (Bernstein, 1967).

JENNY'S CASE ***Variation in training***
For Jenny to become proficient at understanding the manoeuvring of a wire in areas with soft and delicate tissue (such as accessing a coronary thrombosis), her training must include an understanding of these extensive variations. This may include different starting points, tissue types, and patient positions.

For example, Jenny might practice with simulations that vary the angle of vessel entry or the fragility of the surrounding tissue, helping her explore affordances and limitations of her design. These variations enable her to perceive new affordances and refine her design of the wire to accommodate motor responses in realistic, unpredictable conditions.

In sum, engineering education should recognise that adaptive expertise is not only cognitive but also embodied. Through ecologically valid and variable motor learning, learners develop the ability to understand flexible acts and develop solutions that support efficiency in complex, real-world situations.

Building on this understanding, an ecological view suggests that the acquisition of motor skills is shaped by multiple interacting constraints, including the structure and physics of the environment, the physical and mental capacities of the learner, perceptual information available through interaction, and the demands of the specific task at hand (Warren, 2006). From this integrated perspective, skill acquisition results in behaviour that is not fixed but adaptable across varying contexts. Adaptive behaviour is essential because factors such as environment, task demands, and individual goals or motivations change each time an action is performed (Davids et al., 2006). Rather than being imposed by a pre-existing plan, adaptive motor skills emerge from this confluence of constraints and real-time perception (Araújo et al., 2004).

Similarly, Davids et al. (2012) advocate for ecological dynamics when explaining motor learning. Traditional theories of motor learning focus on strengthening internal representations of movements. Researchers following this view emphasise what is acquired in memory to explain behavioural change (Hommel et al., 2001). In contrast, ecological dynamics emphasise the learners' adaptation to their environment. Rather than strengthening internal states, learners establish functional information-movement couplings, tight feedback loops between perception and action, which are foundational to adaptive motor expertise (Davids et al., 2012). In this sense, learning motor skills is shaped by the environment, the physical and mental abilities of the person, and the specific task at hand. Learners then create behaviour that adapts to different situations, by drawing on feedback from the environment which is continuously mediated by their capacities for adaptation. Instead of following a rigid plan, skilled behaviour emerges as a response to the unique demands of each task.

Building on these notions, engineering education should design learning environments that train learners' ability to align intention, perception, and action. As Araújo and Davids (2011) suggest, adaptive motor learning requires learners to continuously adjust information to their action capabilities. According to Gibson, one's actions are guided by ”picking up” information detecting environmental cues that guide action. In this view, action and perception are cyclical: what we do influences what we perceive, and what we perceive shapes how we act (Gibson, 1979).

Therefore, learning tasks in engineering should be designed to include varied information – rich cues, such as changes in gap size, angles, target types, tool affordances, and positioning. These variables invite learners to engage actively with their environment, refining behaviour through repeated cycles of action and feedback. Through this, learners develop rich understandings of the environment they will have to develop solutions for, and which affordances provide opportunities for adaptations for end users.

JENNY'S CASE ***Simulated tasks, variability, and adaptation***

To prepare Jenny for developing biomedical solutions for thrombosis treatment, her educators can provide simulated tasks that reflect real-world variability. For instance, they might alter task constraints such as the material properties of tubing, the positioning of access points, or the pressure levels of simulated blood flow.

By engaging with this material and interpreting the feedback from her problem-solving process, Jenny learns to adapt, refine, and generalise her solutions across situations. Over time, this enables her to explore a range of design possibilities and improve the usability of her engineering solutions in complex clinical environments.

Educating for ecological, adaptable motor skills

The previous sections have shown that adaptive expertise is not just a cognitive trait but an embodied, context-sensitive process. Learners develop adaptive capabilities through the dynamic interplay of perception, action, and environmental feedback. We explored how ecological cognition emphasises perception-action loops, how embodied cognition underscores the importance of sensory and motor engagement, and how ecological dynamics highlight the role of variability in skill development. With this foundation, we will now discuss how educators can translate these principles into concrete pedagogical strategies.

This movement from skill acquisition to skill attunement or skill adaptation requires that the educator changes perspective and allows the learners to explore solutions rather than having them engage in repeated practice. The application of the core practice principle of ”repetition without repetition” underscores the importance of adopting a transdisciplinary approach wherein each learner is positioned at the core of the educator's design endeavours (Otte et al., 2022).

To support the development of adaptive expertise, learners should be challenged to self-organise and adapt coordinative structures. Teaching for adaptability means shifting from instructing learners to perform idealised routines towards helping them interpret and respond to the nuances of dynamic tasks (Araújo & Davids, 2011; Renshaw & Chow, 2019). This highlights the importance of assessing motor behaviour in ecologically valid conditions.

In bioengineering, Ng and Button demonstrated validity evidence of a four-construct model for evaluating movement competence in a large sample of schoolchildren (Ng & Button, 2023). They found that dynamic rather than static tasks maintain the ecological condition which is representative of how users of the model interact in the real world. Through collaborative efforts, engineering educators can craft learning tasks rooted in problem-solving, tailored to address the unique requirements of individual learners. Otte et al. (2020) constructed such a training programme in sports.

The framework known as the 'Periodization of Skill Training' (referred to as the "PoST" framework) offers a valuable model for educators to design training based on an ecological approach (Otte et al., 2020).

The PoST framework outlines three progressive stages of learning:

1. **Coordination Training:** In this phase, learners explore and stabilise relationships among motor skills components. They explore various ways to execute a task and identify functional movement solutions.

2. **Skill Adaptability Training:** Here, learners are encouraged to explore various ways of performing the task, under variations in context, materials, constraints, and goals. The process of movement adaptation and optimisation helps learners refine their capacity to adapt and transfer skills to novel situations.

3. **Performance Training:** This phase focuses on preparing for and maintaining performance stability. Learners consolidate their adaptable responses and integrate performance under pressure (Otte et al., 2020).

By guiding learners through these stages, educators can scaffold experiences that support exploration, variability, and performance under changing conditions. This aligns with the ecological view that learners adapt their behaviour through ongoing perception-action loops in context-rich environments.

Here, a key educational consideration is supervision. Gamborg et al. (2022) propose a supervision framework that differentiates between two modes of instruction:

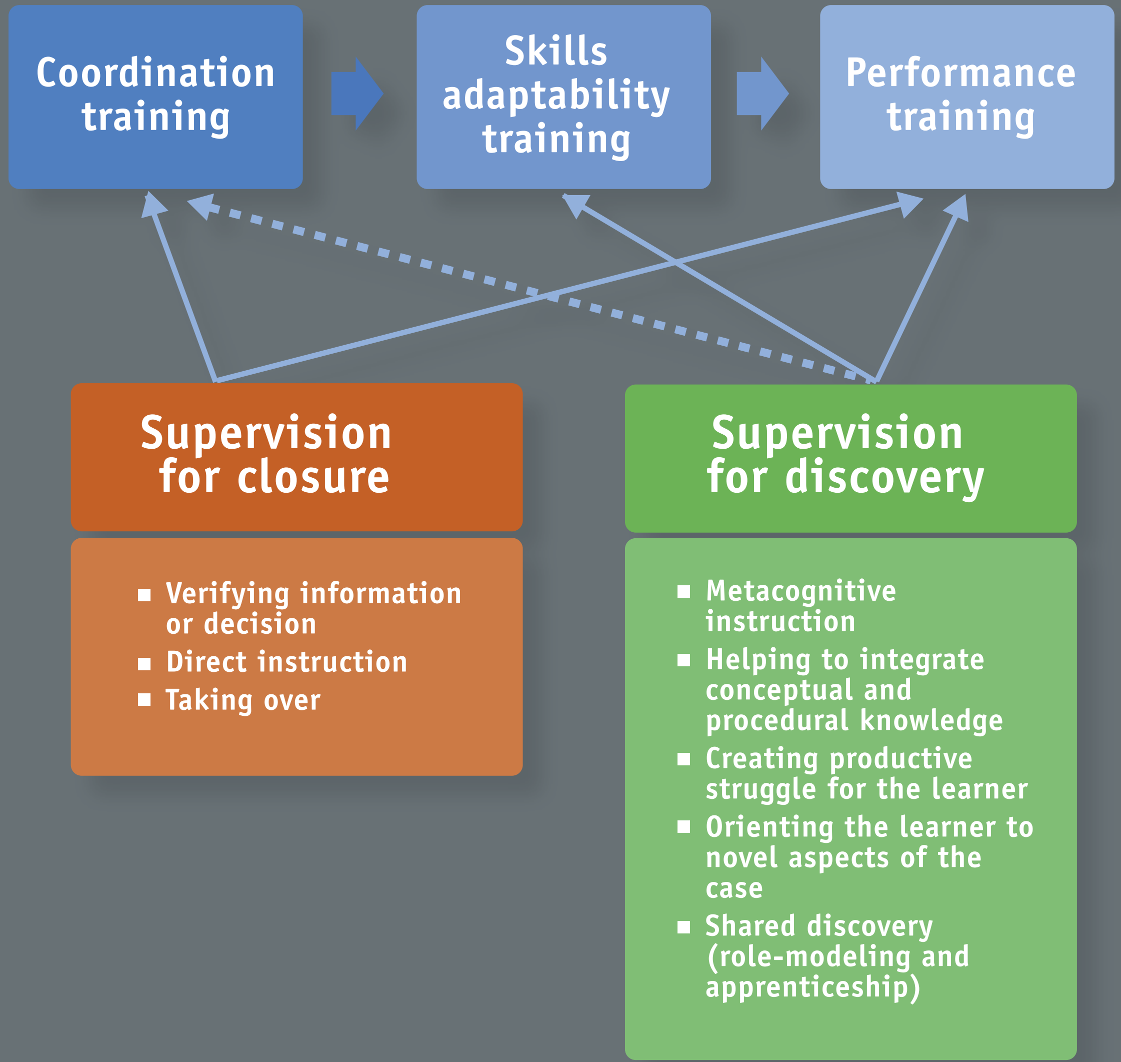
- *Closure:* When the teacher provides direct answers or instructions to a student, resulting in immediate correction, but reduced learner autonomy.

- *Discovery:* When the teacher refrains from immediate correction and instead prompts the learners to reflect, evaluate, and find their own path forward, or invite to shared learning.

In Figure 1 (p.81), we have merged the PoST framework with feedback recommendations for adaptive expertise from Gamborg et al.

The role of supervision for closure is especially important when learners are coordinating movements in the first stage of the PoST model, and

FIGURE 1 INTEGRATING THE PoST FRAMEWORK WITH SUPERVISION FOR ADAPTIVE EXPERTISE



when they are perfecting their skills in real performance environments during the third stage. On the other hand, supervision targeting discovery helps prompt learners' self-reflection and critical thinking by probing, encouraging, and role-modelling to the learners. This type of supervision is especially important during skills adaptability training and performance training to prompt further exploration of skills.

However, it can also be applied with careful intention, to the first stage, when learners exhibit trust and an eagerness to hone their skills. In this way, the figure provides strategies for how to monitor learners performing flexible tasks and provide timely and appropriate feedback. Importantly, supervision was demonstrated to be a shared, ecological practice, which impacted the outcomes of supervision. Here, the study by Gamborg et al. (2022) demonstrated that disclosing the aim of feedback and ensuring consent to approach supervision for discovery was important, as creating a safe space was essential for learners to explore and experiment in the problem-solving process.

Both approaches have value, but over-reliance on closure can limit learners' opportunities to explore and adapt. For developing adaptive expertise, discovery-based guidance is particularly valuable because it mirrors the uncertainty of real-world problem-solving.

JENNY'S CASE ***Supervising for adaptive expertise***

Returning to Jenny's case: when working with simulations to prototype a biomedical solution, her instructor might observe her technique and ask reflective questions rather than correcting errors immediately. For example, the instructor might ask "What challenges are you encountering with the current wire angle?" or "How do you think a different entry point would affect your control?". This encourages Jenny to explore affordances, adjust her strategy, and reflect on how outcomes relate to her intentions.

In conclusion, educators play a pivotal role in fostering adaptive expertise by designing tasks that incorporate variability, encouraging exploratory learning, and modulating supervision strategies. Not only do these practices help learners acquire skills, they also cultivate the flexibility to apply them in novel and unpredictable contexts, a hallmark of adaptive expertise.

Summary and practical guidelines

This chapter argues that adaptive expertise in engineering education is not solely a cognitive endeavour. Rather, it is a dynamic process shaped through continuous interaction between the learners, their body, the task at hand, and the surrounding environment. Drawing from theories of ecological cognition, embodied cognition, and ecological dynamics, we have shown how adaptive expertise emerges when learners engage in perception-action loops, respond to affordances, and practice within variable, context-rich environments.

In engineering education, embodied approaches to learning can enhance the development of sensorimotor schemas, crucial for tasks requiring precision and adaptability, such as biomedical device prototyping or robotics. By simulating real-world conditions that engineers will face, these approaches allow learners to integrate perception, action, and environmental feedback.

JENNY'S CASE ***Simulation in engineering with variability and embodied cognitive adaptation***

If we take the example of Jenny, her task involves manipulation of surgical tools or mechanical components. To support her learning, educators might provide her with prototypes of varying material stiffness and observe how she adapts her techniques. Here, teaching her to do so can be designed with variable constraints (e.g. different materials, positions, or tools), encouraging her to adapt her movements and refine motor skills. This adaptability fosters not only technical competence but also the ability to innovate under changing conditions, essential for solving complex engineering problems. Such embodied learning helps engineers form functional connections between their actions and environmental cues, improving their ability to apply their designs in practical settings.

By shifting focus from mental representations to embodied action and perception, we propose a more holistic view of learning. This view acknowledges that expertise develops not just in the mind but through doing – through acting, sensing, adjusting, and reflecting within specific environments. Educators should design tasks that simulate real-world scenarios, ensuring that learners interact with dynamic variables such as tool manipulation, material properties, and spatial constraints. For example, biomedical engineering learners can engage in hands-on problem-solving activities where motor skills, like for instance hand-eye coordination, are tested in complex environments such as simulating surgical procedures.

Teaching should emphasise variability in tasks to foster adaptability, a key feature of adaptive expertise. Encouraging learners to explore different solutions rather than repetitive practice enables them to develop a deeper understanding of how motor skills and cognitive processes intertwine.

Supervision strategies can shift between providing direct feedback for skill refinement and encouraging self-discovery for innovative problem-solving.

To support the development of adaptive expertise in engineering learners, we offer the following practical guidelines, based on the ecological and embodied learning approach:

1. **Design contextual richness and variability and ensure representativeness of the performance environment:** Design learning tasks that closely represent the complexity of real-world conditions which engineers will face, with changing materials, tools, and constraints. This allows learners to engage with diverse affordances and practice adjusting their actions accordingly. For example, in biomedical engineering, tasks like tool manipulation in simulated surgeries can create realistic scenarios which reflect the challenges that the end users encounter in their professional environments and promote adaptive problem solving within learners.

2. **Emphasise exploration over repetition:** Encourage learners to try different strategies rather than repeating idealised techniques. Incorporate diverse task constraints to promote adaptability. Variation fosters learning through adaptation rather than memorisation, encourages learners to explore different solutions, and enhances their ability to innovate under changing conditions, elicited by these embodied experiences during the engineering process.

3. **Foster perception-action awareness:** Help learners become more attuned to how their actions influence and are influenced by environmental feedback. This helps learners to become aware of idiosyncratic affordances that can help or impede skill development and innovative problem solving, fostering a deeper understanding of task dynamics. This can be supported through discussion, debriefing, and reflective supervision.

4. **Encourage embodied sense-making:** Support learners in recognising how their physical interactions with tools, materials, and bodies contribute to insight and innovation. Reflection on sensory and motor experiences should be integrated into design and problem-solving processes.

5. **Utilise supervision to balance closure and discovery:** Provide feedback that guide learners, when necessary (closure), but also allows space for exploration, decision-making, and reflection (discovery). This balanced approach helps learners develop both precise motor skills and adaptive, innovative thinking.

Through these practices, educators can support learners like Jenny in developing the flexible, responsive, and context-sensitive competencies that define adaptive expertise. In doing so, engineering education becomes not only a training ground for technical skill, but a space for cultivating the ecological intelligence needed to develop and implement solutions for the 21st century that support navigating complexity and innovating responsibly.

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