

**White paper**

# **Neuroscience and learning through play: a review of the evidence**



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# Table of contents

**Introduction • 3**

**Joyful • 6**

**Meaningful • 10**

**Actively engaging • 14**

**Iterative • 16**

**Socially interactive • 18**

**Future directions • 20**

**Closing thoughts • 22**

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# Introduction



In this white paper, our discussion of the neuroscience and biological literature on learning focuses on five characteristics used to define playful learning experiences, joyful, meaningful, actively engaging, iterative and socially interactive (see Zosh et al., 2017). From a neurobiological perspective, these characteristics can contribute to children's ability to attend to, interpret, and learn from experiences.

## The neuroscience literature in brief

Our current understanding of how each of the characteristics of playful experiences can support learning processes is primarily informed by research that concerns typically and atypically developing adults and animal models. Animal models give us some indication of possible mechanisms in the human brain, but it is worth noting that human and animal models are not perfect parallels. Additionally, adult studies provide insights into human cortical networks, but in brains that are less susceptible and vulnerable to environmental forces than those of children. With this in mind, we review the literature while in most cases leaving open considerations for the ways in which each characteristic may affect learning in children. It is also worth noting that while this research shows how the five characteristics may contribute to learning, few studies actually investigate the direct relationship between play and learning. This too remains an area open for future research.

In what follows, we first describe the interconnected nature of learning informing this review. From there, we summarise each of the five characteristics and how they connect with learning, as seen through a neuroscience lens.

## Interconnected and holistic learning

As we dive into the five characteristics of playful experiences, it is important to view the various experiences embodying these characteristics in the larger context of brain development. Our understanding is not that different parts of the brain mature and dictate learning separately, but instead, that each region relies on ongoing and specific external input and connects robustly with other regions of the brain. Overall, the findings illustrate how the five characteristics of learning through play facilitate the development and activation of interconnected brain processes in growing children and support their capacity to learn.

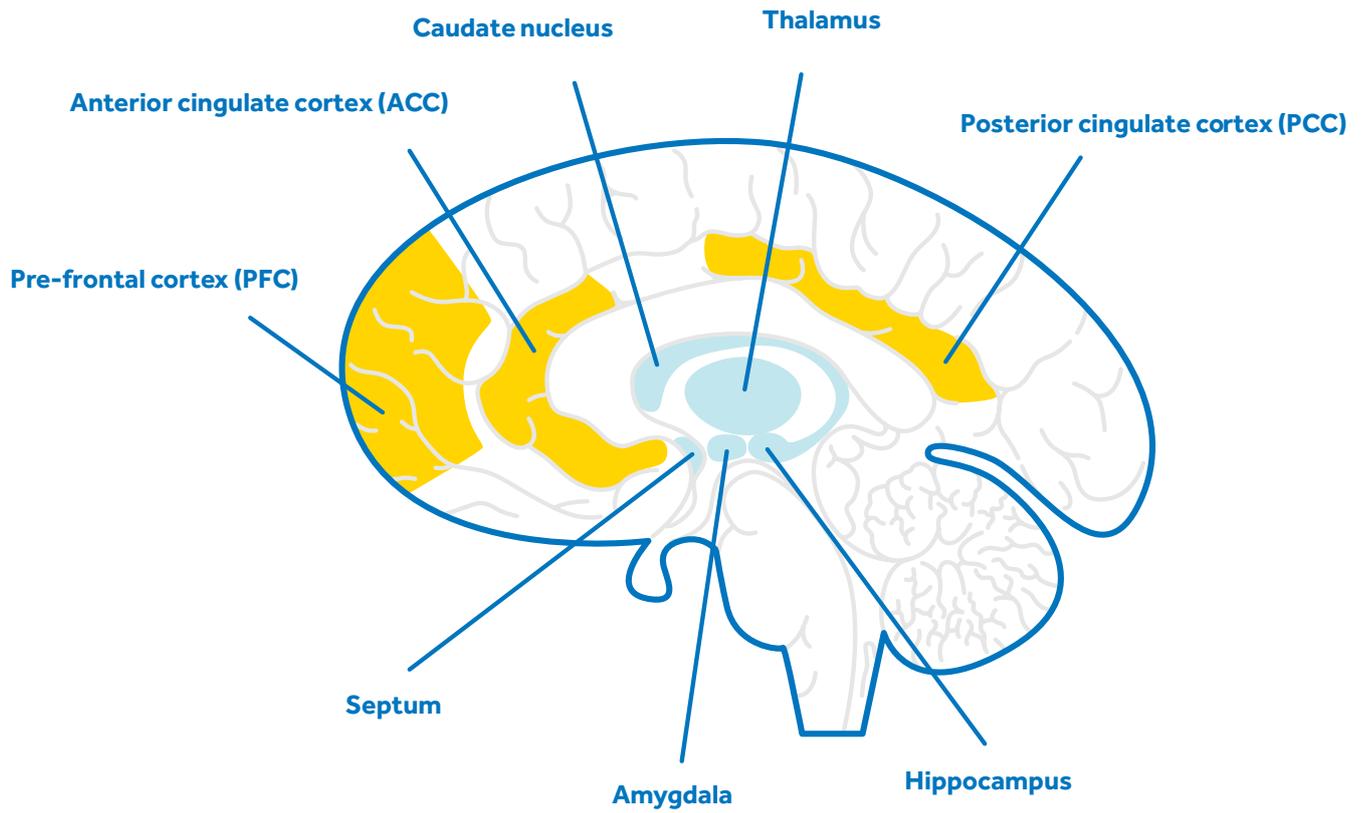
Our understanding of learning in the context of experiences is holistic, meaning that it relates to the development of multiple domains rather than performance on a set of academic measures. Learning in the brain refers to the neural capacity to process and respond to different sensory, or multimodal, inputs, on both basic and complex levels. Inputs across multiple modalities are often helpful, if not essential, for the proper development of learning behaviors for children. Face-to-face interaction with a caregiver, for example, provides an infant with visual, auditory, language, and social-emotional inputs so that she may develop visual acuity, phoneme recognition, facial recognition, and secure emotional attachment (Fox, Levitt, & Nelson, 2010). These outcomes in turn support the development of language, cognitive control, and emotion regulation skills as she continues to grow.

Playful learning experiences characterised by joy, meaning, active engagement, iteration, and social interaction can offer multimodal inputs that stimulate interconnected networks involved in learning (see highlighted areas in the illustration on page 5).

The quality of our experiences therefore affects our development from an early age. With this background in mind, our review explores how each of the characteristics is related to these cognitive processes. The table below summarizes key takeaways from the neuroscience and biological literature for each characteristic.

## Key takeaways

<b>Joy</b>	<b>Meaningful</b>	<b>Active Engagement</b>	<b>Iterative</b>	<b>Socially Interactive</b>
<p>Emotions are integral to neural networks responsible for learning</p> <p>Joy is associated with increased dopamine levels in the brain's reward system linked to enhanced memory, attention, mental shifting, creativity, and motivation</p>	<p>Making connections between familiar and unfamiliar stimuli guides the brain in making effortful learning easier</p> <p>Meaningful experiences introduce novel stimuli linking to existing mental frameworks; processing these stimuli recruits networks in the brain associated with analogical thinking, memory, transfer, metacognition, creating insight, motivation and reward</p>	<p>Active and engaged involvement increases brain activation related to agency, decision making, and flow</p> <p>Active engagement enhances memory encoding and retrieval processes that support learning</p> <p>Full engagement in an activity allows the brain to exercise networks responsible for executive control skills, such as pushing out distractions, that benefit short term and lifelong learning</p>	<p>Perseverance associated with iterative thinking is linked to reward and memory networks that underpin learning</p> <p>With practice, iteration increasingly engages networks related to taking alternative perspectives, flexible thinking, and creativity</p>	<p>Positive caregiver-child interactions help build the neural foundations for developing healthy social emotional regulation and protecting from learning barriers, such as stress</p> <p>Early social interaction promotes plasticity in the brain to help cope with challenges later in life</p> <p>Social interaction activates brain networks related to detecting the mental states of others, which can be critical for teaching and learning interactions</p>



**Medial view of the brain and the areas related to the five characteristics**

# Joyful

Across cultures and animal species, play appears to be a common experience innate to development (Huizinga, 1950; Burghardt, 2010; Smith, 2010). Play can rarely proceed without exhibiting positive affect and joy, the feelings of enjoyment and fun (Huizinga, 1950; Rubin, Fein, & Vandenberg, 1983). Some may argue that positive emotions such as joy have an evolutionary role: they allow us to interact and respond protectively and appropriately to our environment (Burgdorf & Panksepp, 2006).

In the neuroscience literature, the connection between joy and learning has been studied among adults and animals (examples include Burgdorf & Panksepp, 2006; Söderqvist et al., 2011). Our ability as humans to experience joy is regulated by subcortical limbic networks (the light blue area in the illustration on page 5), which are associated with emotional functions and found in animal models as well (Burgdorf & Panksepp, 2006). Networks that involve other brain regions responsible for higher-order processing in learning (cortical regions – the yellow area in the illustration on page 5) respond adaptively to these experiences of emotion (Burgdorf & Panksepp, 2006).

**To adapt is to learn, and joy exists to motivate us to continue adapting to our environment and to learn from it. Joy, it seems, has an important relationship with our propensity to learn.**

## **Learning is emotional and associated with reward**

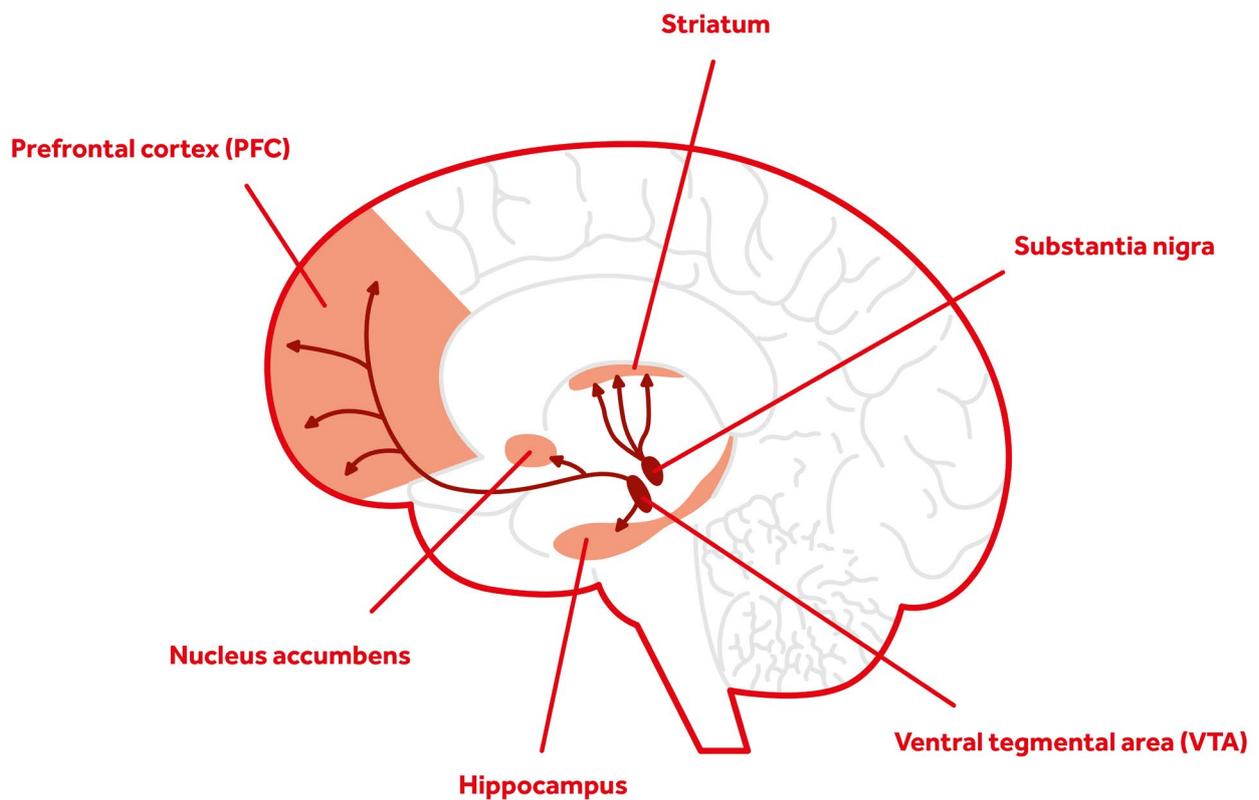
Emotions were previously thought of as secondary to cognition in learning, but developmental and neuroscientific research is quickly revealing that the two are interwoven (Immordino-Yang & Damasio, 2007). To consider emotion and cognition separately would be incomplete. Emotions help to facilitate rational thought by enabling us to apply emotional feedback to our decision-making (Immordino-Yang & Damasio, 2007). The role of emotion in our capacity to take reasonable action in unpredictable circumstances is what Immordino-Yang and Damasio (2007) coin the “emotional rudder” (p. 3). Given the role of emotions in priming us to learn, joy is perhaps one of the most powerful forces.

## **Joy invokes a state of positive affect that enables many higher cognitive functions.**

At a high level, the experience of joy is associated with network changes in the brain, such as increases in dopamine levels, that result in positive emotions. Dopamine is a neurotransmitter that helps regulate reward, pleasure, and emotion in the brain, as well as our actions in response to reward. Effects of dopamine are observed in brain regions identified as part of the reward network, including the midbrain, striatum, hippocampus, and prefrontal cortex (see illustration to the right). Dopamine initiates interaction between these various regions to alter our responses and actions. Bromberg-Martin and Hikosaka (2009, as cited in Cools, 2011) linked the presence of dopamine neurotransmitters on neurons in the midbrain to the process of expecting a reward and seeking information in anticipation of this reward.

The resulting positive affect is linked to a series of cognitive benefits, such as enhanced attention, working memory, mental shifting, and improved stress regulation, that are useful to learning (e.g., Cools, 2011; Dang, Dondé, Madison, O'Neil, Jagust, 2012; McNamara, Tejero-Cantero, Trouche, Campo-Urriza, & Dupret, 2014). There are multiple proposed mechanisms for how dopamine precisely acts on brain

structures (Cools, 2011), however, it is well supported that the presence of dopamine associated with joyful experiences can result in an enhanced ability to process and retain information. Thus, understanding the reward system can help us explore its role in memory, mental shifting, motivation, and creativity, as they contribute to learning.



**Medial view of the brain showing the dopamine pathways**

### **Memory**

Examples of dopamine's effect on memory and learning are found in animal models. Among mice, dopaminergic stimulation in the midbrain while the mice engaged in new spatial environments were associated with greater activity in the hippocampal region, which seemed to improve their recall of the task (McNamara et al., 2014). Furthermore, dopaminergic stimulation initiated while learning the location of a new goal was associated with better activation of hippocampal neurons during resting state. These findings suggest a beneficial role of dopamine while encoding and recalling new information, at least in the case of spatial representation and memory (McNamara et al., 2014).

### **Attention to goals and mental shifting**

Guided by the presence of dopamine during joyful experiences, the regions associated with reward and planning often work in tandem to allow individuals to focus on information relevant to their goals (Vincent, Kahn, Snyder, Raichle, & Buckner, 2008, as cited in Dang et al., 2012). This allows individuals to decide not only which information to attend to, but also plan corresponding goal-directed behaviors. That is, in learning situations, dopamine can help with the mental shifting required as we consider what information to select in order to plan for appropriate goals.

### **Motivation and curiosity**

Intrinsic motivation and curiosity are two traits that readily come to mind in our discussion of the five characteristics of learning through play, but especially in joy, perhaps owing to its spontaneous nature. The literature points to the influence of curiosity and intrinsic motivation in enhanced neural activity as well (Kang et al. 2009). fMRI results show that the more we anticipate a positive outcome, as is often the case when we are intrinsically motivated, the more the activity in these brain structures enhances our ability to retain the information that follows (Gruber, Gelman, & Ranganath, 2014). Small changes in our environmental settings can inspire us to anticipate the learning to come and prime the brain to retain information more effectively (Weisberg, Hirsh-Pasek, Golinkoff, & McCandliss, 2014).

### **Creativity**

Dopamine can enhance processes that have been shown to correlate with creative thinking, such as working memory, but the relation could be more direct. While the exact mechanism is unclear, individual creativity has been found to relate to activation in brain structures associated with the dopamine reward system (Takeuchi et al., 2010), suggesting perhaps that joyful experiences are related to creative thinking.

### **Plasticity**

There is also evidence to suggest that the chemical responses in the brain associated with joyful experiences can influence plasticity, meaning the brain can continue to adapt to new information and environmental inputs (Nelson, 2017; Söderqvist et al., 2011). In this way, joyful experiences that raise dopamine levels in the brain may result in an increased ability to adapt to and learn from new learning situations.



# Meaningful

Learning usually involves moving from the unknown to the known, or from effortful to automatic processing. Meaningful experiences can provide a space for these progressions. Opportunities for contextual learning, analogical reasoning, metacognition, transfer, and motivation can support the development of deeper understanding in such experiences.

## Guiding learning from effortful to automatic

The neuroscience literature illustrates how meaningful experiences recruit multiple networks in the brain to help us make sense of what we learn. Learning new material is assumed to involve two networks (Luu, Tucker, Stripling, 2007): the fast learning system and the later stage of learning (Bussey et al., 1996; Keng and Gabriel, 1998, as cited in Luu, Tucker, Stripling, 2007). The first network assists with rapid and focused acquisition, scanning for inconsistencies or perceived threats. The second network is then recruited to help us put new information in context of our already-constructed mental models (Luu, Tucker, Stripling, 2007).

## Analogical reasoning

Meaningful experiences can serve as opportunities for children to bridge the unknown to models already familiar to them through higher cognitive processes. One form of cognitive process studied in the literature, analogical reasoning, is employed in making connections between the known and the unknown. Analogical reasoning is a type of thinking that helps us see beyond surface-level differences to understand underlying similarities in objects, concepts, or relationships (e.g., understanding that honey from a bee is like milk from a cow, or that we can observe triangles in everyday life). Evidence shows that this type of thinking recruits domain-general regions of the brain operant in abstract thinking, as well as domain-specific regions related to the analogical task at hand (Hobeika, Diard-Detoeuf, Garcin, Levy, and Volle, 2016). The authors suggest that the increased

functional connectivity between these two regions helps connect external stimuli with existing cognitive models.

## Knowledge transfer

When we find learning meaningful, gained knowledge in one domain may be transferred to new and real-world settings. There is evidence to support neurological changes when meaningful experiences provide opportunities for transfer of knowledge, even in the absence of a cognitive task (Gerraty, Davidow, Wimmer, Kahn, and Sohomy, 2014). Moreover, Gerraty et al. (2014) observed that active transfer may be related to activity connecting to regions responsible for memory-related learning and flexible representation. Lastly, decreases in effortful activity in regions associated with encoding new memories have been observed as new knowledge becomes more integrated with prior knowledge.

## Metacognition and confidence

Metacognition is often identified as an important component to self-regulated learning. The ability to recognise and understand our own abilities and thought processes is useful in navigating new contexts, reasoning with new information, and building meaningful experiences. Monitoring ourselves in our environments and making judgments in response rely on the ability to access working memory and predict future performance (Müller, Tsalas, Schie, Meinhardt, Proust, Sodian, & Paulus, 2016). When metacognitive skills allow us to make meaning out of our surroundings and accurate predictions about our performance, our confidence levels increase. It has been suggested that confidence, invoked through metacognitive skills, can prompt reward seeking and improved memory retrieval in meaningful situations (Molenberghs, Trautwein, Böckler, Singer, & Kanske, 2016). Gains in confidence have been associated with increased activity as well as levels of dopamine in regions that are linked to reward, memory, and motor control (Molenberghs et al., 2016).

**Surface learning**  
means we  
memorise key  
facts and principles

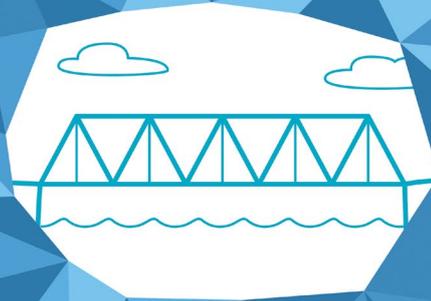


A hexagon has  
six straight sides  
and six angles



A triangle has three  
straight sides and  
three angles – the sum  
of its angles is  $180^\circ$

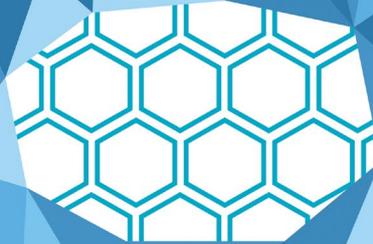
**Deeper learning**  
allows us to connect  
factual knowledge  
with real-world  
experiences and  
really grasp their  
implications



If you make a triangle out of  
three sticks with hinges in the  
corners, it stays rigid. That's why  
triangles are used in bridges,  
cranes, houses and so on.



Notice how snowflakes are  
symmetrical hexagons?  
This shape reflects  
how the crystal's water  
molecules are connected.



Hexagons are useful shapes,  
for example in beehives.  
They use the least amount  
of wax to hold to most  
weight of honey.

### Memory

Meaningful experiences present a blend of familiar and novel stimuli, initiating neural networks involved with novelty processing, memory, and reward seeking exploration that are useful in learning (Bunzeck, Doeller, Dolan, & Duzel, 2012). Studies demonstrate that familiar inputs combined with a novel reward can result in stronger hippocampal activity than familiar stimuli with familiar reward predicted (Bunzeck et al., 2011).

### Insight

One can recall the “aha” moment that often accompanies solving a problem. Researchers hypothesise that forming novel insights requires breaking mental representations to accommodate new information and make meaningful connections (Qiu, Li, Yang, Luo, Li, Wu & Zhang, 2008). Studies show that participants who make a sudden connection exhibit strong activation in cortical regions that are often involved in cognitive control, such as conflict monitoring, inhibitory control and task switching (Carlson, Zelazo, & Faja, 2013; Kizilirmak, Thuerich, Folta-Schoofs, Schott, & Richardson-Klavehn, 2016).

### Reward and motivation

Lastly, some evidence tells us that the formation of new insights are encoded in our memories by activating the brain’s internal reward network (Kizilirmak et al., 2016). Involving the intrinsic reward system activates the hippocampus, which is useful for encoding the meaningful relationship we have just acquired, as well as its later retrieval (Kizilirmak et al., 2016).

Taken together, discovering meaningful relationships in learning through play may build on various cognitive processes, activate the brain’s reward system, and strengthen the encoding of these memories. These can be forceful drivers of learning. It makes sense, then, to provide children with material that is both novel and familiar. We can use this approach to facilitate meaningful experiences for children, guiding them in new explorations through play, for example, that deepen their own relationship with the world.



**What is the difference between a novice and expert? It's not how much they know but their ability to recognise meaningful patterns in that knowledge, see relationships and grasp the bigger picture.**

(DeHaan, 2009)

# Actively engaging



Active engagement in an experience demands both attention and response. Activities and events that are able to elicit active engagement are uniquely pertinent in our discussion of learning through play; it is difficult to imagine that an experience can affect our awareness and thought without being able to captivate us first. Feeling actively engaged is an experience that can be viscerally familiar, as those who are actively engaged in activities often express that they are “in the driver’s seat”, “immersed”, and “losing a sense of time”. The characteristics of this experience are sometimes described as involving agency or inducing flow (Csikszentmihalyi, 1975).

Neurally, active engagement is associated with networks involved in attention control, goal-directed behavior, reward, temporal awareness, long term memory retrieval, and stress regulation. Studies examining the neural correlates of experiences characterised by active engagement implicate the left inferior frontal gyrus (IFG) and left putamen (Ulrich, Keller, Hoenig, Waller, & Grön, 2013). The left IFG has been associated with a sense of control, especially in sophisticated and challenging tasks (Ulrich et al., 2013). As it turns out, the left putamen is often linked to goal-directed behavior (Ulrich et al., 2013). Together, the identification of these neural substrates supports the hypothesis that active engagement recruits higher cognitive processes that are beneficial to learning.

## Agency

Our discussion of active engagement would not be complete without highlighting the role of agency. Perhaps acting as a catalyst to learning, agency helps in guiding our voluntary behaviors, motivating us to seek information and take action. Agency itself can set off a cycle of positive reinforcement, invoking feelings of confidence, progress, and positive affect, leading to

more agency (Kuhn, Brass, & Haggard, 2012). For more research highlighting the link between agency and processes such as memory, see Kaiser, Simon, Kalis, Schweizer, Tobler, and Mojzisch (2013), Holroyd and Yeung (2012), and Jorge, Starkstein, & Robinson, 2010.

## Flow

An important element of experiences that are actively engaging is that they present stimuli at just the right levels; appropriate experiences and inputs can help to immerse us in activities and activate reward networks as long as they are not overwhelming. This is represented in the literature in studies that show decreased neural activity in the amygdala in participants actively engaged in tasks (Ulrich et al., 2013). The amygdala helps with coding perceived threats and plays a central role in stress regulation via the HPA axis (Shonkoff & Garner, 2012). In self-reported flow experiences, those who described feeling more immersed were seen to have greater decreases in their amygdala (Ulrich et al., 2013). These results uphold the relationship between lower amygdala activity and positive emotions that, as discussed previously, can enhance our motivation to learn, and more broadly, between active engagement and our ability to learn.

## Memory

Engaging children at appropriate levels might also play a role in the strengthening memory, particularly short term memory. Some research suggests a correlation between active engagement and memory development and information retrieval (Johnson, Miller Singley, Peckham, Johnson, & Bunge, 2014).

### Executive functions

From behavioral studies with children, we learn that active engagement in an activity is related to executive function skills, such as inhibitory control. Sustained engagement in an activity demands the ability to stay selectively focused on the situation at present, tune out distractions, and hold the information in our heads (Diamond, 2013). We can observe the effects of active engagement on executive function skills (EFs) in a study comparing children assigned to Montessori and non-Montessori schools, which discovered that the Montessori children, who had fewer interruptions during their learning activities, performed better at EF tasks than the other group (Lillard & Else-Quest, 2006, as cited in Carlson, Zelazo, & Faja, 2013). Thus, this evidence poses interesting implications to further study the relationship between active engagement, executive function skills, and learning in young children.



# Iterative

Iterative experiences are characterised by repetition of activity or thought, to potentially discover new insights with each round. Engaging in and building upon this cognitive skill is a critical step to early and lifelong learning. In today's environment of constant change, problem-solving is more salient than ever. Whether the situation calls for building a speedy racecar, troubleshooting a broken household appliance, or working through a challenging project with unrealised answers, iterative thinking pushes us to novel solutions. Iterative thinking is involved in experimentation, imagination, and problem-solving. Through continued trial and error, we also build resilience, an asset to lifelong learning. Our analysis of iterative experiences at the neural level examines many relevant and studied cognitive processes, including perseverance, counterfactual reasoning, cognitive flexibility, and creativity or divergent thinking.

## Perseverance

Any iterative thinking experience involves an element of perseverance. Cortically, perseverance implicates the nucleus accumbens (NA), which plays a central role in the processing of reward (O'Doherty et al., 2004; Nemmi, Nymberg, Helander, & Klingberg, 2016). Connectivity between two regions (the NA and the ventral striatum) has also been associated with perseverance (Myers et al., 2016). Not surprisingly, the ventral striatum is also involved in inhibitory control and cognitive flexibility (Voorn, Vanderschuren, Groenewegen, Robbins, & Pennartz, 2004), both of which are skills that assist us in pursuing our goals. Some research also suggests a correlation between perseverance and positive outcomes in cognitive training for children involving working memory (Nemmi et al., 2016).

## Counterfactual thought and perspective-taking

Beyond perseverance, iterative experiences involve mentally weighing alternative options in one's mind in contrast to reality, or counterfactual reasoning. Counterfactual reasoning helps us rationalise the past, make cognitive and emotional judgments, and adapt behaviour accordingly (Van Hoeck, Watson, & Barbey, 2015), employing a trio of cognitive processes that shapes how we learn. The implicated brain regions are involved in mental representations of multiple scenarios, autobiographical memory, and perspective-taking abilities (Boorman, Behrens, & Rushworth, 2011; Van Hoeck, Watson, & Barbey, 2015). These processes prepare us to make predictions about our decisions and adapt to new information. To do this, the brain interprets external feedback from our decisions and exercises judgements in the future to reinforce favorable outcomes (Van Hoeck, Watson, & Barbey, 2015). Iterative experiences thus nudge us to engage in counterfactual thinking prior to taking action.

## Cognitive flexibility and creative thinking

Weisberg and Gopnik (2013) have also suggested that through similar cognitive computations involved in counterfactual reasoning, employing their imagination allows children to consider past results and possible alternative outcomes to plan future interventions accordingly. Doing so calls for aspects of cognitive flexibility, such as letting go of existing views to change one's perspective based on updated requirements (Diamond, 2013). In contrast to mental rigidity, cognitive flexibility paves the way for creative thinking.

Divergent thinking, a facet of creativity, can act as both a driver and a product of iterative thinking. Research from fMRI studies measuring divergent thinking

in verbal and visuospatial domains consistently implicates the lateral prefrontal cortex (PFC) in creative outcomes (Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010; Kleibeuker, De Dreu, & Crone, 2016). This finding is interesting on two fronts. The lateral PFC is involved with higher cognitive functions, such as cognitive flexibility and problem-solving (Johnson & deHaan, 2015; Kleibeuker, De Dreu, & Crone, 2016), and experiences a surge in growth in adolescence (Johnson & deHaan, 2015). In light of heightened development in the prefrontal cortex during adolescence, this may be a unique period for individuals to engage in creative problem-solving and iterative thinking.

### Plasticity

Evidence may suggest that the more iterative thinking we engage in, the better prepared we become to iterate further. This is perhaps obvious and highly visible in jazz musicians who must improvise at length. In fact, fMRI studies among adult musicians have observed patterns in functional connectivity related to increases in improvisational training (Pinho, De Manzano, Fransson, Eriksson, Ullén, 2014; Gibson, Folley, Park, 2008), suggesting that creative outputs are not necessarily the effortless endeavors they often seem, but can be strengthened by training even through adulthood.



# Socially interactive

Finally, we dive into the role of socially interactive experiences in learning. At its core, learning might be considered a social enterprise. We learn in our interactions with others and within the context of our environment and culture (Vygotsky, 1978). Popular frameworks of child development such as Bronfenbrenner's ecological systems theory remind us that the well-being of an individual is sensitive to the dynamic interactions between social networks, such as caregivers, schools, and society at large (Bronfenbrenner, 1977).

Neuroscience research has shown that from early in development, social interaction plays a remarkable role in shaping our brain and behavioral development (Nelson, 2017). Beginning immediately after birth, children's interactions with supportive and responsive adults (also called serve-and-return interactions) help to build a strong neural foundation in brain regions responsible for the development of basic functional systems such as vision and language (Fox, Levitt, & Nelson, 2010).

Beyond basic sensory functions, social interaction is also critical for the development of higher processes (Hensch, 2016). The same serve-and-return functions that underpin our visual and auditory capacities fuel our cognitive, social, and emotional regulation later in life. Research shows that babies can process an adult's emotional reaction and respond adaptively, such as returning a joyous smile or avoiding an object to which the caregiver shows fear (Happé & Frith, 2014). This sensitivity to social cues sets the neural stage for regulatory processes that have been demonstrated through research and practice to be essential for learning in complex environments.

## **Caring relationships are essential**

The quality of caregiver interactions matters, as they present a major source of social emotional development. Positive caregiver relationships can

buffer children from the deleterious effects of adverse experiences by helping to regulate stress responses, allowing other brain networks to help us navigate through everyday life (Center on the Developing Child at Harvard University (CDC), 2012; CDC, 2016). Under adversity, the brain expends more energy detecting and protecting the individual from possible threat, taking resources away from more long term planning, cognitive development, and self-regulation needed to overcome difficult circumstances (Lupien, Gunnar, McEwen & Heim, 2009).

Another way to underscore the importance of positive and nurturing caregiver relationships in early childhood is to examine what happens to a child in the absence of social interaction. Without supportive, stimulating, and caring relationships, brain function at its full potential becomes a challenge. Children who experience extreme neglect and social deprivation in institutionalised settings exhibit decreased brain electrical activity associated with learning difficulties, as measured by EEG (Nelson, Fox & Zeanah, 2013). Nevertheless, timely and appropriate interventions in which children are placed in environments where they are surrounded by positive and supportive social interactions can help ameliorate or even reverse the negative cognitive, social, and physical effects of neglect.

## **Peer interaction and self-regulation**

Whereas social and emotional systems of children depend primarily on interactions with their caregivers or other caring adults early in life, they are more attuned to their peers later in childhood and through adolescence (Nelson, 2017). Interactions with peers can help children develop skills such as language acquisition, cooperation, and social learning. Social interactions can also provide the context for a child to practice self-regulatory skills, such as control of inhibitions and take appropriate actions, that develop executive function skills (Diamond, 2013).

Neuroscientific and biological studies of play in animals appear to indicate that social interactions during play can help support the development of brain regions and neural networks essential for learning these skills.

Social interactions in rodents characterised as rough-and-tumble play appear to shape the PFC and have an impact on self regulation and planning (Bell, Pellis, & Kolb 2010; for reviews also see Pellis & Pellis, 2007; Pellis, Pellis, & Himmler, 2014). It appears that through playful experiences involving social interactions, juvenile rats and perhaps children develop essential neural networks that are foundational for learning.

### **Adaptability**

Furthermore, social interactions involved in juvenile playful experiences appear to enhance animal adaptability to unexpected circumstances. Indeed, it appears that “the juvenile experience of play refines the brain to be more adaptable later in life” (Pellis, Pellis, & Himmler, 2014, p. 73) by enhancing neural plasticity (Maier & Watkins, 2010; Himmler, Pellis, & Kolb, 2013). Conversely, animals deprived of social play in early in development and adolescence display rigidity and abnormally low levels of social behavior later in their development, even when resocialised (Baarendse, Counotte, O'Donnell & Vanderschuren,

2013; Nelson, 2017). Studies of rats that are socially isolated early in life show that they are more prone to impulsivity, irregular behaviors, and poor decision-making in novel and effortful situations (Baarendse et al., 2013).

### **Detecting mental states**

Social interaction may also help us exercise the mental processes involved with understanding perspectives other than our own even in the absence of prompting (German, Niehaus, Roarty, Giesbrecht, & Miller, 2004). Contexts that provide opportunities to engage in interpreting the mental state of others might sufficiently initiate processes such as theory of mind (German et al., 2004), which can be integral for formal and informal teaching and learning interactions.

Whether from caregivers or peers, these findings highlight the importance of positive, social interactions in establishing healthy development. For this reason, we emphasise the role that socially interactive playful learning experiences can hold in productively shaping a child's developmental trajectory. While more rigorous investigations into play among children are needed to better understand these effects, the coupling of social interactions that are enriching with the neural foundations for learning is one worthy of attention.



# Closing thoughts

There is a rich body of literature establishing the neural correlates of the different facets of learning that align with the five characteristics of playful experiences. This allows us to further explicate how playful experiences can support learning. We find that mechanisms described in the literature show a generally positive cycle. In other words, each characteristic is associated with neural networks involved in brain processes, including reward, memory, cognitive flexibility, and stress regulation that are activated during learning. In turn, the activation of these neural networks serves to prepare a child's brain for further development (Puschmann, Brechmann, & Thiel, 2013). Thus, having experiences that are joyful, help children find meaning in what they are doing or learning, and involve active engagement, iterative thinking and social interaction can provide children with the foundations for lifelong learning.

Our understanding of the neural underpinnings of learning thus far is supported primarily through adult and animal studies. Most of what we know of learning in children comes from behavioural studies in the developmental and cognitive sciences. However, recent advances in non-invasive neuroimaging techniques allow us to observe changes in brain activity among adolescents and younger children in informal settings that are relevant to our exploration.

Using these techniques, future research can seek to validate some of the findings observed among adult and animal studies. In particular, research may be able to experiment in novel settings that are less restricted by static machinery, such as playful experiences themselves. Designing studies using

movement-friendly tools such as fNIRS, and EEG can help us pinpoint specific patterns of brain activity in playful learning experiences in situ. This will allow us to identify contexts that are conducive to learning, the specific ways in which they encourage learning, and for whom the contexts are most productive. Having this more nuanced understanding may help us design neuroscience research that further elucidates the underlying neural mechanisms that can facilitate learning through play.

The direction of the relationship between play and learning, as well as the relationship among the different characteristics of playful experiences, also warrants further exploration. For example, we may find that joyful experiences involve reward systems that incline individuals to engage in creative and flexible thinking; alternatively, it is possible that the opportunity to engage in creative and flexible thinking is what makes playful experiences joyful.

From the perspective of geographical contexts, we also find that research in this area is weighted toward western (e.g., North American and European) settings. While diverse and positive experiences matter for brain development and neural network formation across all cultures, we might seek to better understand how these experiences manifest depending on their cultural contexts. Certain dimensions of culture (e.g., language experience such as bilingualism, (Barac, Bialystok, Castro, & Sanchez, 2014)) might influence children's neural development in ways that shape their learning and cognition. To support a more complete understanding, further research in diverse geographical and cultural contexts is needed.



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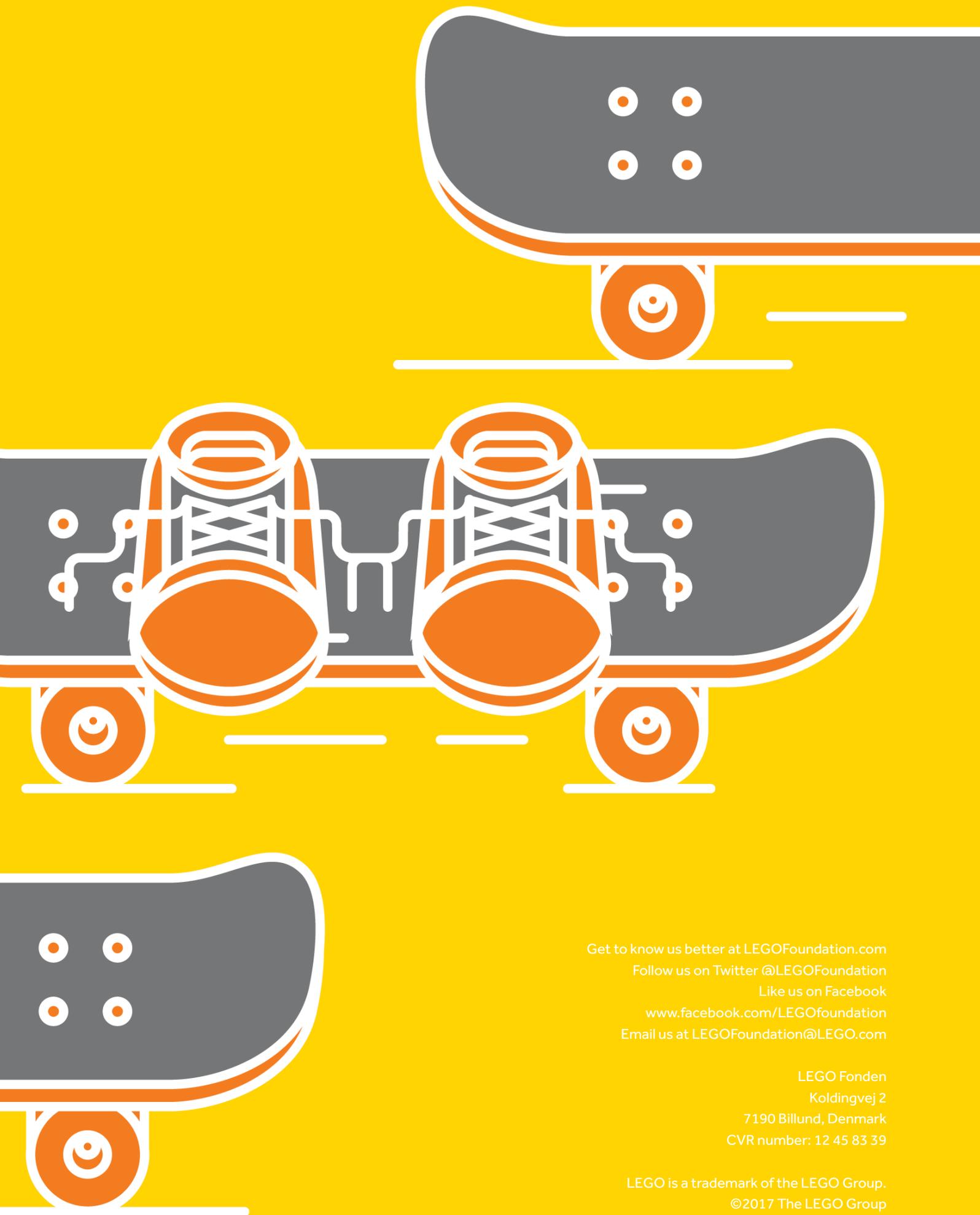
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