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(Review Article)

The impact of robotics on development, of hot and cold executive functions, and their role in improving them in special education

Nikolaos Drakatos * and Antonios Christou

University of Thessaly, Greece.

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Abstract

Executive function (EF) skills are neurocognitive skills that support the reflective, top-down coordination and control of other brain functions, and there is neural and behavioral evidence for a continuum from more "cool" EF skills activated in emotionally neutral contexts to more "hot" EF skills required for motivationally significant tendency reversal. EF problems are transdiagnostic markers of abnormal development. A neurodevelopmental model follows the path from bad childhood events and stress to disturbance of the development of brain systems supporting reflection and EF skills and an increased risk for general psychopathology traits. Educational robotics is generally concerned with researching the effects of building and programming robots on children's learning and academic accomplishment. We recently discovered that engaging in progressively more difficult robot planning and monitoring (ER-Lab) promotes visual-spatial working memory and response inhibition in early childhood during typical development, and that an ER-Lab can be a viable rehabilitative tool for children with Special Needs. Children with Special Needs (SN) had considerably enhanced inhibition skills, and children with attentional impairment had greater gains in inhibition of motor response tasks than children with a language deficiency. The study's findings and future prospects for how ER-Lab programs could become a strong tool in classrooms with special needs children are highlighted. The key also conclusion was that there was a considerable improvement in visuo-spatial attention as well as a significant effect on robot programming skills. According to research, EF abilities can be developed through scaffolded training and are a promising therapeutic and preventive intervention target. Intervention efficacy can be increased by reducing disruptive bottom-up effects like stress, teaching both hot and cool EF skills, and incorporating a reflective, metacognitive component to facilitate far transfer of trained skills.

Keywords: Executive function; Educational robotics; Special needs; Working memory

1. Introduction

The complexity of the EFs and SN relationship may be attributable in part to the fact that EFs are a complicated construct that is explained by various theoretical frameworks. Although different multi-componential models define the main basic EF components (Miyake et al., 2000; Friedman and Miyake, 2017), there is agreement on their role as valuable "tools of learning" for academic skills at different grades (Mitsea et al., 2020). The ability to alter information stored in memory is crucial in language acquisition, decoding, and text comprehension.The ability to inhibit prepotent responses, such as the suppression of compelling thoughts or memories, and resist distractor interference, which is selectively attuned to what we choose, thereby removing attention to other interferent stimuli, allows us to focus on relevant information during reading comprehension or problem solving (Stavridis & Doulgeri, 2018). Finally, the ability to quickly switch between tasks, procedures, conceptual sets, or strategies appears to be related to academic learning (Mitsea et al., 2020). These processes, concern three primary core EFs components: working memory, inhibition, and

* Corresponding author: Nikolaos Drakatos

cognitive flexibility. Inhibition, working memory, and, to a lesser extent, cognitive flexibility have all been demonstrated to be reduced in various types of Special Needs (Stavridis, Papageorgiou and Doulgeri, 2017).

Educational Robotics (ER) is a teaching method that requires students to design, assemble, and program robots through play and hands-on activities. In the 1960s, ER was created by combining psycho-pedagogical cognitive development theories and social learning theories (Drigas, Vrettaros et al., 2005). ER develops a learning environment in which students can interact with both peers and robots at the same time. Most ER studies in schools have examined the impact of ER activities on "STEM" (Science, Technology, Engineering, and Mathematics), with a particular emphasis on robot design and assembly (Papageorgiou et al., 2021). Other research has looked into employing ER as an assistive device to help with motor and social communication issues (Drigas & Karyotaki, 2019). Recent research has looked at how robot programming affects cognitive and learning processes as automonitoring, attention, decision-making, problem-solving, and computational thinking (Chaidi et al., 2021). Nonetheless, the majority of the research lacked experimental designs or quantitative outcome measurements, leaving it unclear which cognitive processes may be considerably improved by ER during childhood (Demertzi, Voukelatos et al., 2018).

2. Cool and Hot Executive function

Executive function (EF) skills are a group of neurocognitive abilities that enable conscious, top-down control of thought, action, and emotion; are required for deliberate reasoning, intentional action, emotion regulation, and complex social functioning; and allow for self-regulated learning and adaptation to changing circumstances (Zelazo, 2015). Early-onset EF issues are a significant component of a wide range of clinical illnesses with childhood or adolescent start, including, Learning disabilities, attention deficit/hyperactivity disorder (ADHD), conduct disorder (CD), autism spectrum disorder (ASD), obsessive-compulsive disorder (OCD) depression, and anxiety (Shi et al., 2019). The ubiquity of EF difficulties across disorders suggests that disruption of EF development may be a common consequence of many different types of developmental perturbation (e.g., genetic/environmental/epigenetic, cognitive/emotional/social), though different types of perturbation may lead to different clusters of symptoms, and different aspects of EF may be implicated in different disorders or within a single disorder. As a result, the presence of EF issues can be considered a transdiagnostic signal of atypical development in general (Beauchaine & Cicchetti, 2019).

According to developmental psychopathology , which takes a developmental systems view of the etiology and life course of atypical behavior, a wide range of variables and their interactions influence biological and psychological development and can result in psychopathology (Drigas, Papoutsi & Skianis, 2021). Childhood adversity is a well-established risk factor for both internalizing and externalizing problems (Humphreys et al., 2019), and evidence suggests that adversity is associated with a general, nonspecific risk for psychopathology (Drigas & Papoutsi, 2021). Furthermore, in a cross-sectional study of 2,395 children aged 6 to 12, performance on a battery of EF measures was connected with risk for a latent general psychopathology factor but not specific variables (Martel et al., 2017).

These findings suggest a developmental pathway that leads from (a) adverse childhood experiences (ACEs) and other sources of stress to (b) disruption of the development of neural systems supporting EF skills and then to (c) an increased risk for general psychopathology, including transdiagnostic features of a wide range of clinical conditions (cf. McLaughlin, 2016). The role of EF difficulties in this developmental pathway can be understood as a result of (a) the fundamental role that EF skills play in learning and adaptation across social and nonsocial contexts, (b) the relative plasticity of EF skills over an extended period of time (i.e., from infancy to early adulthood, with periods of greater plasticity occurring in early childhood and the transition to adolescence), and (c) the hierarchical character of both EF talents and the neural systems that support them.

EF was historically generated from neuropsychological findings of the repercussions of prefrontal cortex (PFC) injury. Today, EF skills are known to be dependent on increasingly well-understood neural circuits involving PFC and other brain regions and they are typically measured behaviorally as three skills: inhibitory control, working memory, and cognitive flexibility (Mitsea, Drigas & Skianis, 2022). Inhibitory control is the conscious suppression of attention (or other responses) to something (for example, ignoring a distraction or ceasing an impetuous remark). Working memory is remembering information and typically modifying it in some way (for example, remembering two integers and subtracting one from the other). Thinking about a single input in numerous ways, for example, while considering someone else's perspective on a situation, is an example of cognitive flexibility. Recent neuroimaging findings show that these three neurocognitive skills activate partially overlapping brain regions, with common activation areas across tasks including frontoparietal control and dorsal attention networks (Duncan, 2013) (see the sidebar titled Neural Activity Associated with Executive Function Skills). These networks differentiate into adulthood, with differences in between-network connectivity depending on the kind of network (Kastritsi et al., 2019). Lower-order, more specialized networks (e.g., sensorimotor networks) have decreased between-network connection with age, but higher-order networks including the PFC have increased.

There is also significant behavioral and neurological evidence that EF skills range along a spectrum from "hot EF" to "cool EF" (Zelazo & Müller, 2002). Whereas cool EF refers to EF skills assessed in relatively emotionally neutral contexts and relies more on neural networks involving lateral parts of the PFC, hot EF refers to EF skills needed in motivationally significant situations and relies more on neural networks involving ventral and medial parts of the PFC. Nejati et al. 2018, point to the role of the hot-cool continuum in EF.

Cool EF can be tested in a variety of ways, including very random or decontextualized activities in a laboratory or clinic. Inhibitory control, working memory, and cognitive flexibility are all examples of cool EF. The dimensional change card sort (DCCS) is an example (see the sidebar titled The Dimensional Change Card Sort: A Measure of Executive Function Skills), a rule use task that requires all three EF skills in early childhood but increasingly serves as a measure of cognitive flexibility as inhibitory control and working memory develop (i.e., these demands become trivial as inhibitory control and working memory develop) (Drigas & Karyotaki, 2016). When tasks like the DCCS and tests of inhibitory control and working memory are utilized in motivationally meaningful circumstances, they can become relatively hot. However, it is the specific requirement of flexibly reappraising whether to approach or avoid a salient stimulus that makes EF hot and involves neuronal networks involving the more ventral and medial parts of PFC (Allan & Lonigan, 2014).

Many measures that require changing the value of specific stimulus-reward connections have been discovered to be dependent on neural circuits connecting the ventral and medial PFC with mesolimbic regions such as the amygdala and striatum (Happaney et al., 2004). Measures of reversal learning (when a previously rewarded approach-avoidance discrimination must be reversed), delay of gratification and delay discounting (when the value of an immediate reward must be reconsidered relative to a larger delayed reward), and extinction (when a previously rewarded stimulus is no longer rewarded and must now be avoided) are some examples. The Iowa Gambling Task (IGT) (Manes et al., 2002) appears to involve both hot and cold EF skills, in which initially advantageous (greater rewards) alternatives are gradually shown to be detrimental (higher prizes but much higher losses), and vice versa.

Cool EF skills (e.g., working memory) also play a role in the IGT (Manes et al., 2002), and given that cool EF skills engage and modulate hot EF skills, relatively complex hot EF tasks, such as the IGT, may activate both hot and cool EF processes (Moriguchi & Shinahara, 2019). Finally, hot EF plays a role in deliberate emotion regulation, which involves modulating approach-avoidance reactions intentionally, including through reflection and cool EF processes, as seen in decentering, psychological distancing, and related metacognitive practices (Travers-Hill et al., 2017).

Individual differences in cool and hot EF skills measured behaviorally in childhood predict a wide range of developmental outcomes, including school performance and social competence in adolescence; college grade point average and graduation ; and physical health (McClelland et al., 2013). The predictive value of EF is frequently greater than that of IQ, and long-term predictions are seen even when controlling for IQ and childhood SES (Duckworth & Seligman, 2005). It is not unexpected, then, that aberrant development of these skills might result in widespread and pervasive obstacles to brain growth and good adaptation. Evidence from young children suggests that, while poor hot EF is more strongly associated with problem behaviors in school (inattentive and overactive behavior), cool EF is more strongly associated with academic outcomes, including math and reading. Groppe and Elsner (2014) studied 1,657 children aged 6 to 11 years and discovered that cold but not hot EF was connected to fluid intelligence. In contrast, other research has indicated that hot but not cool EF is connected to emotional intelligence (Checa & Fernández-Berrocal, 2019). Both hot and cool EF are related to key aspects of social cognition, such as theory of mind (ToM) (Carlson et al., 2004), but evidence suggests that hot EF is more strongly related to emotion-related social cognition, such as ToM stories involving affect (Wilson et al., 2018) and ToMmental state/emotion recognition (Kouklari et al., 2019).

Johnson (2011) proposes that the development of EF skills involves the experience-dependent functional specialization of EF skills and the neural networks that support them. Initially, confirmatory factor analysis of adults' performance on a variety of cool EF measures suggested three correlated latent variables (Miyake et al., 2000), but subsequent research has supported a hierarchical, bifactor model involving a common EF latent variable as well as updating (working memory) and shifting (cognitive flexibility) variables (Friedman & Miyake, 2017). In contrast to adult studies, several studies with young children have found that cool EF measures load onto one or two factors (inhibitory control and working memory and appears to become differentiated by middle childhood or adolescence as a bifactor structure involving common EF and multiple specific factors emerges (Cirino et al., 2018).

In contrast to the delayed differentiation within cool EF, differences between hot and cool EF have been reported rather early in development, at least when hot EF is measured using tasks including the requirement to delay approaching a tempting reward (Willoughby et al., 2011). For example, research with children as young as 2 years old (Bernier et al., 2012) have indicated evidence for hot and cool factors in children's performance on batteries of EF measures. Willoughby et al., (2011) discovered support for hot and cool EF variables in a study of approximately 750 children aged 4-5 years. A recent study of 1,900 children aged 2 to 5 years old from varied socioeconomic backgrounds found support for hot and cool EF variables across numerous direct behavioral measures of each construct (Montroy et al., 2019). However, as with cool EF, there have been inconsistent results (Allan & Lonigan, 2014), which are most likely due to the hot EF measures utilized. It is also possible that as the brain circuitry underlying them is engaged and activated, hot and cool EF become more robustly distinguished. A pattern of age-related differentiation between EF skills and other non-EF cognitive functions has also been discovered during childhood and adolescence, as measured by the NIH Toolbox Cognition Battery (Mungas et al., 2013), and this pattern may reflect use-dependent specialization of neural systems.

3. Educational robotics for the development of executive skills such as vision, spatial abilities, planning, and problem solving.

Many schools are using educational robotics (ER) as an innovative learning environment that allows students to acquire higher order thinking skills and talents, as well as tackle complicated challenges (Drigas & Karyotaki, 2017). It is a strong and adaptable teaching and learning tool that engages students in robot construction and control activities using particular programming tools. Students in an ER exercise typically work in groups to solve challenging challenges. Students receive quick feedback on their efforts and learn how to deal with difficult circumstances in a real-world environment through iterative design and testing (Drigas & Karyotaki, 2019).

Recent research suggests that the ER can be used to boost transversal skills such as thinking, problem solving, metacognition, programming, and teamwork (La Paglia et al., 2017; Drigas & Koukianakis, 2004; Drigas & Koukianakis, 2006). Programming a robot's behaviors to achieve a goal necessitates the capacity to mentally foresee the action, select the proper technique, and continuously update it. Choose the right process and keep it up to date. Programming small mobile autonomous robots into the physical environment necessitates planning, precision in language use, hypothesis formulation and testing, the capacity to identify action sequences, and a number of other skills that appear to mirror what thinking is all about. Furthermore, working with programmable robots allows children to test the robots' actions in the real world with all of its variables, such as indeterminacies and typical uncertainties of the environment (as opposed to simulation in virtual contexts where everything is still predefined) and their own reasoning strategies. The feedback (both positive and negative) produced by the robot/environment interaction necessitates ongoing adjustment of the programming algorithms (Demertzi, Voukelatos et al., 2018).

Children must apply procedural thinking and understand the logic of instructions in order to construct a successful program. When developing a program, children consider next, before, and until, all of which are components of sequencing—particularly temporal sequencing. Given these features, robotics activities can improve mental processes associated with the cognitive domain of the Executive Functions, such as problem solving, planning, working memory, inhibition, mental flexibility, action initiation, and monitoring (Chaidi et al., 2021). The term "EF" refers to a group of adaptive, goal-directed, top-down mental processes that are required when you need to focus and pay attention and when a spontaneous response would be insufficient (Lytra & Drigas, 2021). Executive functions enable "mentally playing with ideas, thinking before acting, meeting novel, unexpected challenges, resisting temptations, and staying focused" (Scarpa et al., 2006).

4. Educational Robotics Improves Executive Functions in Children with Special Needs at School

Children with Special Needs (SN) require special educational and instructional procedures due to social, physical, or mental issues. They are a highly diverse population in terms of neurofunctional, behavioral, and sociocognitive characteristics. Children with SN may have sensorial or motor disabilities, Autism Spectrum Disorders, Mild or Severe Intellectual Disabilities, and specific neurodevelopmental disorders such as Attention Deficit Hyperactivity Disorder (ADHD), Specific Learning Disorders, Specific Language Disorders, or other unspecified difficulties (McFarland et al., 2018). Despite this variation, it is now well known that specific cognitive control processes, such as Executive Functions (EFs), are frequently disrupted across developmental disorders and special needs (Mitsea et al., 2020). EFs have been found to be frequently altered in children with socioeconomic disadvantages, Mood Disorders, Attention Deficit Hyperactivity Disorder (ADHD), Autistic Spectrum Disorder (ASD), Language and Learning Disabilities, Down Syndrome (DS), neuromuscular disorders, and Cerebral Palsy (CP) (Di Lieto et al., 2017a; Battini et al., 2018; Peng and Fuchs, 2016; Stavridis & Doulgeri, 2018). The causal relationship between EF impairment and Special Needs is far from linear, as three main scenarios can be proposed: in some cases, a clear EF deficit is part of the "core cognitive difficulties" of a specific SN group; in other cases, only subtle difficulties are found; and finally, it is possible that the clinical or social problem itself causes the EF impairment (Astrea et al., 2016).

Given the predictive role that EFs play in academic achievement, early interventions in children with SN on working memory and inhibition may avert cascade consequences on quality of life, school attendance, and social functioning. Among the new technologies implemented for educational purposes, Educational Robotics (ER) has been used in educational settings with typically developed children to improve problem solving, planning, and computational thinking (Stavridis, Falco & Doulgeri, 2020), basic EFs components (Di Lieto et al., 2017b), and academical learning, particularly in the area of Science, Technology, Engineering, Mathematics and STEM. ER is a learning approach based on the design, assembly, and programming of robots that draws on constructivism and constructionism theories of learning and cognitive development as well as social learning theories (Papageorgiou et al., 2021).

Recently, a growing number of studies have offered ER to SN people in order to provide additional learning and social inclusion chances. Examples of the use of robots in clinical and educational settings have been documented, including learning difficulties, motor disorders, intellectual disabilities, autism and ADHD (Cheng et al., 2018; Bargagna et al., 2018; Stavridis et al., 2022).

Indeed, educational robots have been used in the SN population to investigate specific cognitive functions, such as cognitive flexibility in children with ASD or the effect of robot-mediated learning (Krishnaswamy et al., 2014; Drigas & Dourou, 2013). Krishnaswamy's study compared the impact of robotic training on visual motor skills in children with learning impairments and visual motor delays. The findings revealed that children who engaged in ER activities improved their visual-motor skills more than children who followed the standard curriculum. Another study by Conchinha revealed two single instances who improved their learning, language, and integration by participating in ER activities with Lego Mindstorm (Conchinha et al., 2016). Finally, after discovering that intense, challenging, and entertaining ER training (ER-Lab) organized by incremental difficulty improved visuospatial working memory and inhibition in typical preschoolers (Di Lieto et al., 2017b), we validated the ER-Lab in a clinical setting with a group of children with Down Syndrome (Bargagna et al., 2018).

The results shown above, suggests that the ER-Lab is a versatile instrument for cognitive improvement in SN and normally developing children; fact, it may be effective for personalizing therapies in neurodevelopmental disorders. The ER-Lab looks to include various qualities to increase the efficacy of the EFs trainings at the same time. ER-Lab activities can be intense, challenging, and adaptable to individual functioning, thus acting in the proximal development zone (Drigas, Vrettaros et al., 2005); it can promote several EF components, either simultaneously or separately, because robot programming requires sequential reasoning before acting by inhibiting impulsive responses, holding and manipulating visuo-spatial and verbal information in memory, and shifting between different commands/rules. ER activities can be carried out in any school setting, creating a group setting and an appealing learning environment, thereby promoting students' interest and motivation, allowing for interventions that focus not only on cognitive empowerment but also on social and emotional inclusion. Finally, the ER-Lab assures the presence of a mentor who may tailor the activity to the specific needs of the subject (Stavridis, Papageorgiou and Doulgeri, 2017).

Last but not least, we emphasize the significance of all digital technologies in the special educational domain and executive functions development, which are very productive and successful, and how they facilitate and improve assessment, intervention, and educational procedures via mobile devices that bring educational activities everywhere [61-63], various ICTs applications that are the main supporters of education [64-78], and AI, STEM, and ROBOTICS that raise educational procedures to new performance levers [79-80] as well as via friendly games [81-83]. Additionally, ICTs are being improved and combined with theories and models for cultivating emotional intelligence, mindfulness, and metacognition [84-105], accelerates and improves more the educational practices and results, especially in special education treating domain and executive functions development.

5. Conclusion

A simplified model of the development of psychopathology in childhood and adolescence links ACEs and other sources of toxic stress to the disruption of neural systems supporting reflection and both hot and cool EF skills, and then to an increased risk for general, transdiagnostic features of a wide range of clinical conditions. The role of EF difficulties in this developmental pathway can be explained by (a) the fundamental role of EF skills in learning and adaptation, (b) the hierarchical nature of both EF skills and the neural systems that support them, and (c) the relative plasticity of EF skills over time. According to research, both hot and cool EF skills hold potential as a general target for therapeutic and preventive intervention. Indeed, a growing amount of evidence demonstrates that EF skills can be developed through scaffolded training. It is argued that intervention efficacy can be increased by minimizing disruptive bottom-up forces such as stress, and that skills training with a reflective, metacognitive component can aid promote distant transfer of trained skills. The current study's findings support the usage of robotics-based educational systems to stimulate the use of specific cognitive and attention talents. This study backs up the premise that Educational Robotics activities have an impact on executive functions since they may be used to build higher-level control components including forecasting, planning, and problem solving. Indeed, this study provides quantifiable data for analyzing the effects of a robotics laboratory on children's transversal high-level cognitive abilities. In general, the findings revealed that participation and improvement of logical reasoning ability enable participants to foresee and plan the sequence of activities required to complete a certain behavioral task.

Compliance with ethical standards

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Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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