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The Impact of Authentic Early Childhood STEM Experiences on Cognitive Development

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Abstract

Early experiences in STEM education can contribute to positive cognitive development in young children. When students have the opportunities to play, inquire, follow their interests/curiosities, develop STEM identities, be creative, and operate within concrete/contextualized STEM explorations, they will experience expansive cognitive growth. Cognitive benefits include expanded thought capacity, increased creativity, better problem-solving abilities, a developing capacity for research, better exploration processes, and better observational powers. Implications for practice and recommendations for educators are discussed.

Keywords: STEM, Child Development, Cognitive Development, Early Childhood, Play, Inquiry

Introduction

The general development of a child is a complex, dynamic process that is interdependent on several factors. According to Richter et al. (2019), experiences in a child's early years can significantly "shape biological and psychological structures and functions in ways that affect health, well-being and productivity throughout the life course" (para. 1) Strong child development across general domains, which include the cognitive, social, emotional, and physical realms is crucial for long-term academic success, individual thriving, and social/emotional maturity (US Department of Health and Human Services, 2022; Diamond, 2010). Though a healthy general development is critical to a child's future success, experiences in STEM, especially during the vital early period of neuroplasticity (first 2-3 years of life), can serve as a catalyst for expansive cognitive growth. Ulu and Kiraz (2014) suggest that not only do early experiences in STEM provide opportunities for expanding thought capacity and creativity, but these experiences can foster the child's capacity for problem-solving, researching, exploring, and observing through a child's own unique engine of curiosity. A child's interests are the key to unlocking these critical developmental pathways (Neitzel et al., 2019). Furthermore, future curriculum in STEM areas can be built directly from a child's original interests and inquiries while promoting exploration, experimentation, and STEM learning (Guarrella et al., 2022).

Due to the importance of quality initial STEM experiences in a child's cognitive development, stakeholders, including parents and early childhood educators, need to consider the axiological characteristics for high-impact pedagogical approaches and experiential activities. In other words, what constitutes quality or authentic STEM experiences, and how will those experiences maximize a child's cognitive development? Furthermore, how can educators and parents prioritize/foster these experiences? The purpose of this paper is to explore the factors that impact healthy development through STEM activities while also providing recommendations for educators and parents. Since authentic STEM experiences are an important early pathway for constructive cognitive development, stakeholders must be aware of the critical significance of play, interest-based/child-led inquiry, identity development, creativity, and concrete/contextualized activities. These traits, when fostered in early childhood STEM experiences can lead to increased observational capacity, divergent thinking and creative innovation, problem-solving, critical thinking, engagement in science and engineering practices, conceptual development, and meaningful retention (Firdaus & Rahayu, 2019, Stone et al., 2019). In addition, these types of holistic, child-centered, inquiry and play-based activities will foster healthy cognitive development, increase STEM engagement and identity, and create pathways for future STEM success.

Factors that Promote Positive Cognitive Development through STEM Activities

Play represents a strong mode for positive, general development across all domains. According to Yogman et al. (2018), play is essential to development as it "enhances brain structure and function and promotes executive function" (para. 2) Furthermore, play is necessary for the development of problem-solving skills, collaboration, creativity, and prosocial behaviors (Yogman et al, 2018). However, the role that play performs in STEM is not as well researched as its general benefits to the developing child. The literature is clear that play in STEM areas affords children the opportunities to increase their imagination as it relates to STEM subjects, ponder new meanings and possibilities, engage in STEM talk, and increase the capacity for authentic inquiry (Vartianinen & Kumpulainen, 2020). Furthermore, both unstructured and structured play in STEM are critical components of impactful instructional models that will foster meaningful and relevant learning experiences (Kennedy & Tunnicliffe, 2022). Play in STEM promotes high-level engagement, inclusion, and holistic skill development through activities that promote joy, meaning, and intrinsic motivation (Parker et al., 2022). Play also offers pathways for children to build their understanding of STEM concepts as they engage with materials in divergent ways while exercising their authentic inquiry (Stone et al., 2019). For example, children playing with magnets can discover concepts like attraction and repulsion, and they can discover that magnets will stick to metals. This process can occur holistically and organically through their free play and the employment of their personal inquiries. Play opportunities in STEM should involve plenty of time and materials for free explorations, questioning, investigation, and the testing of hypotheses.

Early experiences in STEM should also be driven through the natural engine of a child's curiosity. Harackiewicz et al. (2016) suggest that a child's interest is one of the most "powerful motivational process that energizes learning," and it is particularly needed in STEM subjects that often do not capitalize on students' interests (para. 1). Interest is also crucial for healthy cognitive development. McIntyre et al. (2021) suggest that interests are a significant factor in cognitive processes and that it is possible to dramatically increase STEM engagement and learning by making the content "interest relevant" (para. 12). In terms of cognitive development, interest plays a key role. When a child's interest is piqued, they have an elevated awareness that drives further investigation, and increases the construction of new knowledge while facilitating positive cognitive ontogenesis (Van Aswegen & Pendergast, 2023). For parents and early childhood educators, the goal is to create the right circumstances and contexts where children will develop interests in STEM areas. Creating these environments that foster interest include triggering situational interest through new experiences, maintaining situational interest through relevant connections, encouraging emerging individual interests through independent inquiries and choice, and aiding an enduring/well-developed interest that is deeply connected to identity in STEM (Renninger & Hidi, 2015; AIR, 2024). In one major study, relevance of the STEM content and the agency of the child were found to be significant factors in children developing situational and individual interest (AIR, 2024). Curiosity is an innate and powerful mechanism that can and should be fostered in the early STEM experiences of children. Curiosity represents the pathway for children to explore their interests in individual, dynamic ways.

Closely related to interest, authentic inquiry in STEM areas will provide children an opportunity to explore and investigate through meaningful activities. These inquiries are crucial to children's work as scientists, engineers, and mathematicians. As children actively engage in exploring the world through inquiry, they come to better understand it, and therefore the child is a scientist, even from birth (Shrager & Carver, 2012; NRC, 2012). Inquiry processes, especially in developing young minds involve observations, wonder about the world, process-oriented explorations, questioning, investigations, identifying patterns, working collaboratively, and sharing ideas (Worth, 2010). Furthermore, inquiry approaches will foster critical thinking, communication, collaboration, and creativity (Spector & Ma, 2019). Perhaps most importantly, the self-creation of knowledge through independent and individually owned explorations "can activate deeper cognitive processing and improve long-term retention compared to the passive reception of information” (Kaiser et al., 2018, para. 1). Further supported by research in cognitive psychology, maximum open-endedness (of the inquiry activities) and high self-creation (of the child) have been demonstrated to benefit long-term learning (retention) and application (Kaiser et al., 2018). Inquiry process is deeply active and should naturally involve engagement through science and engineering practices. Furthermore, inquiry provides opportunities for organic/meaningful integration. Inquiry is most potent when the questions and processes belong to the individual child and are driven by their curiosity.

In addition to play, interest, and authentic inquiry, cognitive development through STEM activities is influenced by the creation of a positive identity in STEM subjects. STEM identity is a key to building a strong scientific literacy (Brown et al., 2005). Not surprisingly, interest is a significant attribute in constructing a robust STEM identity, as children begin to feel a sense of belonging through their interest-driven activity (Kim, Sinatra, & Seyranian, 2018). Furthermore, the lack of a STEM identity can lead to disengagement, which weakens future prospects and activity in STEM areas (National Inventors Hall of Fame, 2024). According to one study, students develop metacognitive awareness through a strong STEM identity, and opportunities for experiential, open-ended STEM explorations contribute to students’ strong problem-solving skills in STEM contexts (Huvard et al., 2020). Moreover, a sense of belonging and STEM identity are crucial factors in students developing a high motivation, practical STEM skills, and future success in STEM careers (Mulvey et al., 2023). In order to develop a strong STEM identity, young children need plenty of opportunities to engage with STEM toys, play and imagine, authentically inquire, explore through their curiosity, investigate their interests, and operate in carefully designed STEM contexts that promote open-ended explorations with educators as a guide and facilitator of meaningful processes. Children also need opportunities to think critically, innovate, think divergently, problem-solve, and persist through challenges. By developing a positive identity and a strong sense of belonging, children will not only learn to persevere through challenges, but they will cling to STEM as a defining trait of their existence.

Creativity and its link to STEM experiences, though not substantially researched, is an emerging factor in cognitive development and future STEM success. In one study, children who were engaged in STEM activity, and who enjoyed STEM experiences, demonstrated a significantly higher level of creativity than students who were not engaged or did not enjoy STEM (Borg Preca et al., 2023). Furthermore, when students are engaged in project-based STEM activities, they operate in the creative realms of adventurousness, curiosity, imagination, resolution, elaboration, and novelty (Hanif et al., 2019). These realms are integral to healthy cognitive development. According to Khalil et al. (2019), creative cognition is rooted in executive functioning and positive moods increase creative thinking. Furthermore, healthy development is dependent on cognitive, motivational, and emotional traits that support creative ideation (Khalil et al., 2019). This study is highly interrelated to the aforementioned work on play and identity in that play specifically provides opportunities for executive functioning, and identity development helps individuals attach positive moods/motivational elements to STEM activities. When considering that STEM is a highly creative set of interrelated fields, and that its progress relies heavily on the imagination and the creativity of its pupils (Morgan et al., 2023), it is of the utmost importance that young children have the opportunities to engage creatively within STEM. However, STEM teaching and learning experiences have often been reduced to a rigid, positivistic system of prescribed endeavors that preclude students’ creativity and dynamic cognition. Therefore, it is necessary to shift away from or greatly reduce STEM methods that favor memorization and convergent activity. Instead, young children need to engage creatively within STEM experiences, and they can do so by operating as innovators, imaginers, and players within their own internally created representations of STEM concepts. Here, the teacher or parent can operate as a guide and facilitator but must resist becoming the giver of knowledge. The capacity to think limitlessly through play, especially, can have a profound impact on the direction and success of the child.

Finally, STEM education should be context-driven and utilize concrete experiences to engage learners. Concrete experiences in STEM offer opportunities for children to see concepts represented through experiments, manipulations, and investigations that favor direct activity rather passivity. Furthermore, concrete explorations demonstrate the concept through physical knowledge involving visual/spatial representations, touch, and the ability of the learner to work through the concept using physical (concrete) media. These experiences are most effective when they allow the child to build from previous knowledge and fit within Dewey's principle of interaction which states that external factors need to align with internal factors (Baroody, 2017). In other words, the context must be meaningful and relevant to the individual child, interest is a significant factor, and the experience must be concrete and tied to the student's level of familiarity. According to Piaget's theory of cognitive development, "problem solving and cognitive development progress from establishing object permanence, causality, and symbolic thinking with concrete (hands-on) learning to abstract thinking and embedding of implicit to explicit memory development" (Malik & Marwaha, 2023, para. 7). There is a continuum of learning and development that varies by child, and the capacity for abstraction is built over time from the operation of the individual in the concrete realm and the development of symbolic thinking first. It would belie the generally accepted belief that students can learn effectively through whole-group (often abstract) instruction when context, interest, and individual readiness are such significant factors in the learning process and can vary widely from individual to individual. Furthermore, STEM activities must involve a relevant context through which students engage in problem-based or project-based learning, inquiry, and design through real-world examples (Sutaphan & Yuenyong, 2019). The isolated, discrete, sterile environments where STEM concepts are efficiently delivered through a prescribed curriculum and standardized teaching disallow the flexibility for individual, context-driven explorations that are highly divergent and dependent on the learner's interests/understandings.

Discussion and Implications

Authentic STEM learning should be characterized by frequent opportunities for unstructured play (in STEM domains), capitalize on a child's natural engine of curiosity to explore the world, foster the child's unique interests, allow for multiple authentic inquiries and engagement in science and engineering practices, create a strong STEM identity, promote creativity and creative thinking, and be characterized by meaningful, relevant, concrete, and context-driven explorations. When young children operate in authentic STEM experiences, they have the opportunity for expansive cognitive growth and development. Children increase observational capacity, divergent thinking and creative innovation, problem-solving, critical thinking, engagement in science and engineering practices, conceptual development, and meaningful retention. Early childhood educators and parents should be aware that an overly academic focus on STEM, meaning strict programs that emphasize content knowledge memorization, are too limiting. In fact, they can be detrimental not only to the child's development of a STEM identity, but to their cognitive development. Even programs that are active (hands-on) can be ineffective if they are too teacher-directed with little to no opportunity for children's authentic inquiry, play, creativity, and connections to personal relevance. From an early age, the child should be immersed in STEM materials, toys, language, and contexts (e.g. trips to the science museum or space center, etc....). The child should have complete control over the direction and magnitude of their wonder with the adult(s) serving as a guide only. Educators and parents should recognize the interests of the child and foster those interests through material and experiential activities. Potential barriers for formal STEM programs include a standardized curriculum program, standards, a lack of teacher training/understanding, and a lack of adequate materials for exploration and investigation.

Conclusion

STEM learning is too often characterized by teacher-directed, overly content-oriented, prescribed procedures that are derived from standardized curricula. In these types of environments, young children are often not afforded the opportunities to play, authentically inquire, follow their interests, or develop conceptual understandings through concrete, context-driven explorations. Based on emerging research in cognitive development, a more holistic, child-led STEM approach is recommended, especially for early childhood programs. Children should have freedom and plenty of time/resources to freely play with STEM materials (obviously in a safe manner). Through their play, they will discover certain concepts, build foundations for future instruction through personally relevant experience, exercise inquiries and scientific process, and develop a potentially strong identity in STEM. Furthermore, by fostering a more child-centered STEM approach, children will have opportunities to engage and progress cognitively by expanding thought capacity and creativity and increase their capacity for problem-solving, researching, exploring, and observing. Quality STEM experiences in early childhood can provide pathways for children to develop STEM understandings, build strong foundations for constructing future knowledge, create a robust identity in STEM, and lead to future success in their academic and career endeavors. Educators and parents should be aware of the nature of the impact of these types of authentic experiences and advocate for better practice.

References

American Institutes for Research. (2024). *STEM interest and engagement (STEM IE) study*. https://www.air.org/project/stem-interest-and-engagement-stem-ie-study

Baroody, A. (2017). The use of concrete experiences in early childhood mathematics instruction. In J. Sarama et al., (Eds.) *Advances in Child Development and Behavior* (Vol. 53), (pp. 44-87). Elsevier.

Borg Preca, C., Baldacchino, L., Briguglio, M., & Mangion, M. (2023). Are STEM students creative thinkers? *Journal of Intelligence, 11*(6). https://doi.org/10.3390/jintelligence11060106

Brown, B., Reveles, J., & Kelly, G. (2005). Scientific literacy and discursive identity: A theoretical framework for understanding science learning. *Wiley InterScience*. https://onlinelibrary.wiley.com/doi/pdf/10.1002/sce.20069

Diamond, A. (2010). The evidence base for improving school outcomes by addressing the whole child and by addressing skills and attitudes, not just content. *Early Education and Development*, 21(5), 780-793.

Firdaus, A., & Rahayu, G. (2019). Effect of STEM-based learning on cognitive skills improvement. *Elementary School Forum*, 6(2), 198-207.

Guarrella, C., van Driel, J., & Cohrssen, C. (2022). Science education in early childhood education-Are we approaching a cure for the state of chronic illness? *Research in Science Education*, 52, 37-45.

Hanif, S., Wijaya, A., & Winarno, N. (2019). Enhancing students' creativity through STEM project-based learning. *Journal of Science Learning*, 2(2), 50-57.

Harackiewicz, J., Smith, J., & Priniski, S. (2016). Interest matters: The importance of promoting interest in education. *Policy Insights from the Behavioral and Brain Sciences*, *3*(2) 220-227. http://dx.doi.org/10.1177/2372732216655542

Huvard, H., Talbot, R., Mason, H., Thompson, A., Ferrara, M., & Wee, B. (2020). Science identity and metacognitive development in undergraduate mentor-teachers. *International Journal of STEM Education*, 7(31). https://doi.org/10.1186/s40594-020-00231-6

Kaiser, I., Mayer, J., & Malai, D. (2018). Self-generation in the context of inquiry-based learning. *Frontiers in Psychology*, 9. https://doi.org/10.3389/fpsyg.2018.02440

Kennedy, T., & Tunnicliffe, S. (2022). Introduction: The role of play and STEM in the early years. In S. Tunnicliffe & T. Kennedy (Eds.) *Play and STEM Education in the Early Years* (pp. 3-37). Springer.

Khalil, R., Godde, B., & Karim, A. (2019). The link between creativity, cognition, and creative drives and underlying neural mechanisms. *Frontiers in Neural Circuits,*13. https://doi.org/10.3389/fncir.2019.00018

Kim, A., Sinatra, G., & Seyranian, V. (2018). Developing a STEM identity among young women: A social identity perspective. *Review of Educational Research*, 88(4), 589-625. https://doi.org/10.3102/0034654318779957

Malik, F. & Marwaha, R. (2023). Cognitive development. *StatPearls*. https://www.ncbi.nlm.nih.gov/books/NBK537095/

McIntyre, M., Gundlach, J., & Graziano, W. (2021). Liking guides learning: The role of interest in memory for STEM topics. *Learning and Individual Differences,* 85. http://dx.doi.org/10.1016/j.lindif.2020.101960

Morgan, R., Kneebone, R., Pyenson, N., Sholts, S., Houstoun, W., Butler, B., & Chesters, K. (2023). Regaining creativity in science: Insights from conversation. *Royal Society Open Science*. http://dx.doi.org/10.1098/rsos.230134

Mulvey, K., McGuire, L., Mathews, C., Hoffman, A., Law, F., Joy, A., Hartstone-Rose, A., Winterbottom, M., Balkwill, F., Fields, G., Butler, L., Burns, K., Drews, M., & Rutland, A. (2023). Preparing the next generation for STEM: Adolescent profiles encompassing math and science motivation and interpersonal skills and their associations with identity and belonging. *Youth & Society,* 55(6), 1207-1230. http://dx.doi.org/10.1177/0044118X221085296

National Inventors Hall of Fame. (2024). What is a STEM identity? https://www.invent.org/blog/trends-stem/stem-identity

National Research Council. (2012). *A framework for K-12 science education*. National Academies Press.

Neitzel, C., Alexander, J., & Johnson, K. (2019). The emergence of children's interest orientations during early childhood: When predisposition meets opportunity. *Learning, Culture and Social Interaction*, 23. http://dx.doi.org/10.1016/j.lcsi.2019.01.004

Parker, R., Thomsen, B., & Berry, A. (2022). Learning through play at school-A framework for policy and practice. *Frontiers in Education*, 7. https://doi.org/103389/feduc.2022.751801

Renninger, K., & Hidi, S. (2015). *The power of interest for motivation and engagement*. Routledge.

Richter, L., Black, M., Britto, P., Daelmans, B., Desmond, C., Devercelli, A., Dua, T., Fink, G., Heyman, J., Lombardi, J., Lu, C., Naicker, S., & Vargas-Baron, E. (2019). Early childhood development: An imperative for action and measurement at scale. *BMJ Global Health*. http://dx.doi.org/10.1136/bmjgh-2018-001302

Shrager, J., & Carver, S. (2012). *The journey from child to scientist: Integrating cognitive development and the education sciences*. American Psychological Association. https://doi.org/10.1037/13617-000

Spector, J., & Ma, S. (2019). Inquiry and critical thinking skills for the next generation: From artificial intelligence back to human intelligence. *Smart Learning Environments,* 6(8). https://doi.org/10.1186/s40561-019-0088-z

Stone, B., Lorentsen, L., & Schmidt, M. (2019). Exploring the role of free play in elementary science. In M. Han & J. Johnson (Eds.) *Play and Culture Studies V. 15: Play and Curriculum*. Lanham, MD: Hamilton Books.

Sutaphan, S. & Yuenyong, C. (2019). STEM education teaching approach: Inquiry from the context based. *Journal of Physics: Conference Series*. http://dx.doi.org/10.1088/1742-6596/1340/1/012003

Ulu, E., & Kiraz, A. (2014). Science education and cognitive development in updated 2012 pre-school curriculum. *Procedia – Social and Behavioral Sciences,* 136, 438-451.

US Department of Health and Human Services. (2022). Office of Early Childhood Development. *About section*. https://www.acf.hhs.gov/ecd/about

Van Aswegen, E., & Pendergast, D. (2023). The impact of interest: An emergent model of interest development in the early years. *Early Child Development and Care,* 193(13-14), 1335-1349. http://dx.doi.org/10.1080/03004430.2023.2245575

Vartiainen, J., & Kumpulainen, K. (2020). Playing with science: Manifestation of scientific play in early science inquiry. *European Early Childhood Education Research Journal,* 28, 490-503.

Worth, K. (2010). *Science in early childhood classrooms: Content and process*. Collected Papers from the SEED (STEM in Early Education and Development) Conference May 2010, University of Northern Iowa.

Yogman, M., Garner, A., Hutchinson, J., Hirsh-Pasek, K, Golinkoff, R. Baum, R., Gambon, T., Lavin, A., Mattson, G., Wissow, L., Hill, D., Ameenuddin, N., Chassiakos, Y., Cross, C., Boyd, R., Mendelson, R., Moreno, M., Radesky, J., Swanson, W., & Smith, J. (2018). The power of play: A pediatric role in enhancing development in young children. *Pediatrics,* 142(3) https://doi.org/10.1542/peds.2018-2058