Spatial Exploration

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This paper records my design of an educational digital technology for children and it reflects the theory and research that I have explored when making each design choice. The final design product is an iPad game called “Spatial Exploration” which aims to enhance children’s spatial intelligence. The whole design process includes four steps, they are 1) observing and interviewing my possible users to find more design opportunities, 2) rapid prototyping based on user needs, 3) finding useful theory and research that supports my design, and 4) determining and modifying the final design to ensure that it is age-appropriate and suitable for child development. The interrelations and interactions of each step contribute a lot to the design formation. The paper consists of four parts. Firstly, I introduce the importance of media technology in children’s brain development and education, and how sociocultural influences contribute to design choices. Secondly, I provide an overview of my digital technology and related research that supports the learning objective. Thirdly, I describe a typical user scenario to leave readers a general impression of how the technology would be used. Finally, I demonstrate the design details together with design rationale to provide readers with a more comprehensive understanding of how each design element functions.

Importance of Media Technology in A Child’s Life

According to the National Scientific Council on the Developing Child (2008), the quality of a child’s early environment and the availability of appropriate experiences at the right stages of development are crucial in determining the strength or weakness of the brain’s architecture, which, in turn, determines how well he or she will be able to think and to regulate emotions. The architecture of the brain depends on the mutual influences of genetics, environment, and experience (National Scientific Council on the Developing Child, 2008, p. 2). Genetics provide the basic plan for brain's architecture through basic properties of the nerve cells and basic rules for interconnecting nerve cells within and across circuits. Axon elaboration and synapse formation as well as axon and synapse elimination are mechanisms that have been shown to alter circuit architecture during sensitive periods (Knudsen, 2004, p. 1415). The sensitive periods for neural circuits that perform low-level analyses of sensory stimuli tend to end before or soon after birth (Jones, 2000). In contrast, the sensitive periods for high-level circuits that process sophisticated aspects of the world, such as communication signals (including language) or the interpretation of facial expressions, end much later in development (Newport, Bavelier, & Neville, 2001). Because low-level circuits mature early and high-level circuits mature later, different kinds of experiences are critical at different ages for optimal brain development (Black & Greenough, 1986). However, impoverished early experience can have severe and long-lasting detrimental effects on later brain capabilities (National Scientific Council on the Developing Child, 2008, p. 4). When designing this media technology for children, it is necessary to provide age-appropriate experience so that it can promote their brain development and learning.

In addition to brain development and education, it is important to take sociocultural influences into consideration when designing digital technology for children. Guided participation may be widespread around the world, but with important variations in arrangements for and communication with children in different cultures (Rogoff, 1990, p. 110). To understand development, we must examine children's skills and interaction with their parents in terms of the function of such skills in achieving locally valued goals, conscientiously avoiding the arbitrary imposition of our values on another group (Rogoff, 1990, p. 117). Cultural variations can influence how parents and children collaborate in children's socialization, and the roles of other social partners, like siblings and other children, grandparents, and the community. When designing children's technology, we need to consider the cultural aspects, like different outcomes of universal activities and the cultural variance of joint participation and interaction.

In conclusion, it is necessary to take into account biology, personal experiences, and culture when designing digital technology for children. This principle is fundamental and guides me through the whole design process.

Design Objectives & Significance

From previous observation of two kids who are 3 years old and 5 years old, I find both of them are especially interested in construction games like Lego and Minecraft. In addition, they all enjoy physical activities and digital games that provide natural interaction. According to the interview of parents, they notice that their kids show improvement in many aspects, like body control and language skills, after interacting with these activities and games. Although I understand that appropriate experiences at the right stages can strengthen brain's architecture, I am still curious about what kind of experiences can strengthen what kind of capabilities and how to determine that these experiences are age-appropriate. Also, I am curious about what kind of scientific research can explain the content of my observation and interview. To find the answer, I did some research about children development milestone, brain and cognitive development, physical activity and modern technology, benefits of construction games, and etc. These research findings contribute a lot to the formation of my digital technology and the learning objective. There are two keywords extracted from these research findings and comprise the core content of my design; they are spatial intelligence and Augmented Reality. In the following, I will provide an overview of my digital technology and explain how spatial intelligence and Augmented Reality related to the learning objective.

Spatial Intelligence

What is spatial intelligence? Spatial intelligence, or visuo-spatial ability, has been defined as the ability to generate, retain, retrieve, and transform well-structured visual images (Lohman, 1996, p. 3). We use visual-spatial skills frequently in daily activities. For example, activities like playing construction games, and ability to tell left and right, and even the way of cutting a bagel to make it fit in the toaster are all good opportunities to practice spatial skills (Newcombe & Frick, 2010, p. 109). There are many pieces of research showing the importance of spatial skills. The cognitive prerequisites for reading and number depend on language development, perceptual development, and spatial development. A child with poor spatial skills will have more difficulty in acquiring symbolic number (Goswami & Bryant, 2007, p. 17). Also, there is some research showing the link between spatial thinking and STEM education. One factor accounts for the correlation is that STEM fields directly call on these skills; that is, they require analyzing and imagining transformations of spatial relations (Uttal, Miller, & Newcombe, 2013, p. 367). For example, modern chemistry depends on thinking about the functional role of chemical spatial structures, ranging from relatively simple molecules to complex proteins and polymers (Kastens & Ishikawa, 2006).

If spatial intelligence is theoretical important in children's future, then the question is whether children can be educated to maximize their potential in this domain? The answer is yes and there is much evidence showing that spatial thinking can be improved. A focus on spatial skills should likely begin in the first 5 years of life, given evidence that early education generally pays the biggest dividends for later achievement (Heckman, 2006). Then, what should we do to develop children's spatial skills? Two particularly important and well-studied skills are the ability to imagine transformations of the orientation of objects (e.g., mental rotations) and the ability to imagine the consequence of observer movements around arrays of objects (i.e., perspective taking) (Newcombe & Frick, 2010, p. 104). Caregivers and educators can then provide children with spatial language that may help them categorize and abstract relevant aspects of their spatial environment, draw their attention to analogies and differences, or simply motivate thought and exploration of space (Newcombe & Frick, 2010, p. 109).

Augmented Reality

There are some pieces of research showing that Virtual and Augmented Reality can be used as spatial ability training tools. VR and AR technologies offer unique possibilities to display and manipulate three-dimensional objects in space, making them ideal tools to study spatial ability (Dünser, Steinbügl, Kaufmann, & Glück, 2006, p. 3). One study on training spatial ability with AR shows that augmented reality can be used to develop useful tools for spatial ability training and measuring spatial ability directly in 3-D space would be more desirable than traditional spatial ability measures (Dünser et al., 2006, p. 6). Compared with Virtual Reality which provides a completely virtual environment, AR allows the users to see the real world, with virtual objects superimposed upon or composited with the real world (Azuma, 1997, p. 2). The property that AR enhances a user's perception of and interaction with the real world matches with my original idea of allowing physical exploration of the real world, that's why I decide to incorporate AR instead of VR to this design. In addition, AR can be used to enhance children's learning experience and there are already some practices about applying AR to education. Construct3D is a three-dimensional geometric construction tool specifically designed for mathematics and geometry education (Kaufmann & Schmalstieg, 2002). It is based on the mobile collaborative augmented reality system and there is evidence supporting that Construct3D encourages experimentation with geometric constructions and improves spatial skills. There are already many applications of AR in higher education settings and compulsory levels of education for motivating students. Target groups like early childhood education and Vocational Educational Training (VET) are potential groups for exploring the uses of AR in future (Bacca, Baldiris, Fabregat, & Graf, 2014, p. 146). The digital technology presented in the paper can be viewed as the exploration of AR in childhood education.

Overview of Digital Technology

As mentioned above, my digital technology aims to enhance children's spatial intelligence and incorporates the technology of Augmented Reality. It uses the platform of iPad. In some tasks that require interaction with the physical world, the camera will open and capture images in real time. There are some image recognition algorithms that can be used to detect the edges of different objects and compute their geometrical shapes (Lefevre & Livet, 2012). The game is targeted at children aged between 6 to 8 according to their brain development, social cognition, and etc. The details of choosing this age range will be elaborated in the part of the design rationale. After interacting with the game, children will have better understanding of geometries, space composition, spatial languages, and etc. Also, they will have the ability to imagine transformations of the orientation of objects (e.g., mental rotations) and the ability to imagine the consequence of observer movements around arrays of objects.

There are three levels included in the game. Each level has different complexity and enhances different spatial skills. Level 1 is the prerequisite for the following two levels which means children have to complete all the tasks in the first level in order to enter into the following levels. Level 1 is called "learn basic concepts" and each task refers to learn one basic three-dimensional geometry. These geometries could be cube, pyramid, cylinder, sphere, and etc. After finishing all the tasks of level 1, children will be able to build the connection 2D images and 3D objects and learn the name of many geometries. Level 2 is called "find similar objects in your house". By using AR technology, children are instructed to find objects in their house that have a specific shape of cube, cylinder or sphere. This level even provides the collaboration mode so that children can play the game together with their peers while they still need to focus on their own tasks. This level aims to encourage children's social interaction, enhance the inhibitory control, and make them understand that many items have geometric shapes. Level 3 is the most difficult one; children need to move different geometries distributed in the space and compose them together according to a given composition on the screen. After playing this level, children will have a deeper understanding of the composition of complex items and learn how to use spatial languages to describe the relationship between two objects. Also, they will have better space sense and fine motor skills since they need to navigate their space and move the virtual objects accurately.

User Scenario

My typical user is a 6-year-old boy whose name is Parker. He lives in Austin, Texas, with his parents and siblings. Jacob is his older brother and he is 8 years old. Bailey is his older sister and she is 10 years old. And their mother Jessica homeschools the kids. Parker loves playing construction games like Minecraft and Lego, and he really enjoys physical activities. His mother uses the game "Spatial Exploration" as a teaching method for homeschool. Sometimes Parker can play the game with his two older siblings at home and he really enjoys it.

Jessica loves staying together with her children and she homeschools the kids. She is enthusiastic about education and she believes that technology can enhance children's learning experiences. One day, she finds an application named "spatial exploration" which claims that the game can enhance children's spatial intelligence. Before getting touch with the game, Jessica only has the general impression that spatial intelligence is something fundamental in children development. But she has no idea about what it exactly means to children's future, let alone how to improve it. After reading the game description, she begins to understand why spatial intelligence is important to children's future and realize that she can use to game to improve children's spatial skills. Then she decides to incorporate the game as part of his teaching methods for the kids. Every day she allows Parker interacts with the game for some time.

When Parker opens the game, he sees the home page which shows three levels. One of them is open and the other two are locked. Every time he clicks on the locked buttons, he will be informed to finish all the tasks in level 1. Entering into level 1, there is a 2D image of a cube together with a 3D cube which he can rotate. Since he can rotate the 3D object, he can observe it from different directions which helps him learn geometry quickly. After learning all the geometries, there is a test that requires him to match several 2D images with corresponding 3D geometries. If he can successfully finish the test, he will be able to enter the next level.

Level 2 uses the technology of Augmented Reality and requires him to find objects similar to a specific geometry in his house. Since Parker is new to this level, there will be some instructions on the screen to guide him how to use AR. For example, he needs to hold the iPad in front of the objects and then point to the screen and click on the one that has a geometric shape. After following these steps, he can successfully add one object to his geometric warehouse. The more he has collected, the higher grades he can get. This level even has the collaborative mode and Parker really enjoys playing it with his siblings. In the collaborative mode, each person will be assigned a task of collecting objects with different geometric shapes. In order to successfully pass the game, they need to focus on their own tasks and avoid clicking on geometries that belong to other people's tasks. If each person can collect the required number of objects within the given time, their collaboration will be considered successful and each person will be given a present in the game.

Level 3 is more complicated than level 2 and it also uses the AR technology. There will be a geometric composition comprised of several geometries on the screen. And from the iPad screen, you can see several geometries distributed in the space. The mission is to move these distributed geometries and create a composition same as the one on the screen. When moving different geometries, Parker will get some instructions like "put the red cylinder above the yellow pyramid". After interacting with this level, Parker learns how to use some spatial languages like above, below, left, and right to describe the relationship between two objects. Also, he learns how to navigate through space in the AR environment and masters some fine motor skills.

Both in level 2 and level 3, there will be an avatar on the screen. Parker can interact with the avatar any time he wants. The avatar can provide him with suggestions, answer his questions and be a good accompany with him. Parker can even customize the appearance of the avatar by using different geometries. After playing with the game, Parker will have a better understanding of space and be able to use some spatial words to describe the relationship of two objects. Jessica can find that his son has improvement in solving math problems especially the geometry questions. Also, she finds that Parker has a better understanding of abstract concepts now since he is able to visualize them in his mind.

Design Rationale

In the above parts, I have provided an overview of the digital technology design and the learning objective. They are supported by some pieces of outside research that I have explored in the field related to spatial intelligence and augmented reality. In the following, I will talk about design details about the game and user interfaces. And I will use the theory and research from previous lectures and readings to explain why I make these design choices.

To ensure the digital technology is suitable for children aged between 6 to 8, I examine how spatial abilities develop at different ages. There is a four-stage development of spatial intelligence across the lifespan. Stage 1 is raw pattern ability which appears from an early age. Children are able to complete puzzles and begin to understand graphic road signs when they are 3 years old (Diezmann & Watters, 2000, p. 304). Stage 2 is understanding a symbol system. At age 6, children are beginning to display spatial intelligence like understanding the relationship between the stairs and the levels of the house (Diezmann & Watters, 2000, p. 305). It is a suitable time for children aged between 6 to 8 to capitalize on their spatial ability through some experiences in the digital technology. But these tasks in my digital technology would be too difficult for children aged between 3 to 5 since their brain development hasn't been mature enough to deal with these tasks.

When designing for children, we should take the differences and similarities between children and adults into consideration. Some key differences include challenge, feedback, trust, and change (Gelman, 2014). More specifically, kids delight in challenge and conflict at a micro level; they love visual and auditory feedback whenever they do anything in a digital space; they are much more trusting than adults and learn from experience; they change pretty quickly so that design should focus on a small age range to increase usage and appeal (Gelman, 2014).

That's why I design the digital technology for a small age range of 6 to 8. Following Gelman's principle, I combine playing and learning together in the design and provide age-appropriate feedback. Spatial exploration is an iPad game using the technology of augmented reality. Considering the cultural influences, the game is suitable for families who are familiar with technology whether as an entertainment or education tool. It is suitable for families that can provide joint-play and guided-participation. When designing the game, I incorporate the element of “leveling up”. There are three levels in total and the complexity will gradually grow as the level rises. In the following, I will describe the theory and research that supports my design according to different levels. For example, Level 1 aims to teach basic concepts and I apply Norman’s theory to the interface design. Compared to level 1, level 2 is more complicated in both contents and reasons for design choices. As for level 2, I will talk about pillars of educational apps, executive function, digital representation, and etc.

Level 1

Norman’s theory. Level 1 is the most fundamental part as it is designed to teach children some basic concepts of geometry. There are several user interfaces included in this level; one is used to help children build the connection between 2D images and 3D objects and another one is used to test whether children have mastered the skill. The design of user interfaces follows the principles of signifiers, affordances, maps, and feedback. The term affordance refers to the relationship between a physical object and a person (or for that matter, any interacting agent, whether animal or human, or even machines and robots) (Norman, 2013). Since the digital technology that I design is an iPad game and it incorporates AR technology, there are two kinds of affordance here. Children can play with iPad in an interactive way like touching and clicking on the screen which is impossible on other platforms like laptop and desktop. Such nature of iPad decides the format of this game and supports affordance between children and the game, just like what Norman says “whether an affordance exists depends upon the properties of both the object and the agent” (Norman, 2013). In addition, augmented reality provides the affordance of interacting with the physical world. Children can see the real world from the screen and with some support from image recognition algorithms, they can even click and choose specific objects of the physical world. The term signifier refers to any mark or sound, any perceivable indicator that communicates appropriate behavior to a person (Norman, 2013). When the 3D object is presented on the screen, I add a dynamic arrow around it to suggest that we can rotate it. This is one example of the signifiers. Mapping is a technical term, borrowed from mathematics, meaning the relationship between the elements of two sets of things (Norman, 2013). For example, there is mapping between the 2D images and the corresponding 3D objects. Feedback is some way of letting you know that the system is working on your request (Norman, 2013). When the kid is rotating the 3D object, there will be sound effects similar to moving objects in real life. Also, if the kids correctly answer the question, they will get the feedback like "congratulations". Otherwise, they will hear the sound effect that suggesting their answer is wrong, so that they can realize it immediately and try another different option.

Executive function skill. Working memory (WM) refers to a child's ability to hold, update, and manipulate verbal or nonverbal information in the mind over short periods of time (Obradović, Portilla, & Boyce, 2012, p. 326). Infants can briefly retain a single item or perform simple two-step procedures, but the capacity to hold and manipulate multiple units of information in the mind emerges in preschool children and continues to develop as children grow older (Garon, Bryson, & Smith, 2008). After children have learned several geometries, there will be a test on the screen that requires them to match the given 3D objects with the corresponding 2D images. This test aims to help children develop their working memory.

Level 2

Gelman's design principle. According to Gelman (2014), the design rules for 6-8 year olds are different from design rules for 3-5 year olds. When designing for children aged between

6 to 8, you should explain, explain, and explain again because they feel better prepared to excel when having all the rules established before they begin (Gelman, 2014). Another rule is to up the complexity. These can be explained by their gradually mature executive function skills that they can better inhibitory control, working memory and cognitive flexibility. When kids turn 8 or so, they like games that provide more of a complex “journey,” where they can continue to learn, grow, and discover over time (Gelman, 2014). Also, children older than 8 gradually have mature executive function skills. Executive functioning represents a cornerstone of early childhood development, as it encompasses a set of core skills that enable children to exert control over their thoughts, feelings, and behavior (Obradović et al., 2012, p. 341). That’s why, for children between 8-10s, we should think about activities that require dexterity, skill, accomplishment, and the ability to improve over time (Gelman, 2014). Some 8-10-year-olds like this and they’re not necessarily looking for a game or app that they can master right away.

I incorporate the two design rules for 6-8 year old children in the digital technology to make sure it is age-appropriate. For example, considering children are unfamiliar with the operations in AR environment, I provide full guidance on how to collect objects before they begin the game of level 2. There will be some white lines showing the geometric shape of one object in their house, and then there will be a hand on the screen telling them that they should click on that object. Finally, there will be more interface showing that the object has been successfully added to the warehouse. Through this guidance, children will understand the basic rules to start the game.

Pillars of educational apps. Humans learn best when they are actively involved (“minds-on”), engaged with the learning materials and undistracted by peripheral elements, have meaningful experiences that relate to their lives, and socially interact with others in high-quality ways around new material, within a context that provides a clear learning goal (Hirsh-Pasek et al., 2015). That's why I decide to include the evidence-based pillars of learning in the game design.

The first one is active learning. According to Hirsh-Pasek et al. (2015), "to qualify as active in our pillar, children cannot simply tap or swipe, but rather must be minds-on" (P. 8). For example, children need to rotate the 3D objects on the screen to see it from different orientations. Also, they need to pay attention to the connection between 2D images and 3D objects since they need to answer some questions that randomly appear.

The second one is engagement in the learning process. According to Hirsh-Pasek et al. (2015), children's engagement with the learning process means avoiding the myriad distractions potentially available on-screen and allowing for sustained engagement sufficient to meet the learning goals (P. 12). In order to ensure the coherence of the learning experience and the child's engagement, I try to avoid extraneous animations, sound effects, and tangential games which will not add to the child's understanding of the primary content. For example, I use narration instead of the pop-up text to make sure that children can focus on their tasks without unnecessary distraction. And the narration itself can be useful in helping children to understand their tasks and providing the more engaging environment.

The third one is meaningful learning. A reasonable proxy might be to consider the quantity and quality of connections between the app experience and the wilder circles of a child's life (Hirsh-Pasek et al., 2015, p. 15). Level 2 allows children to find that many items in our life have a basic geometric shape. It helps children build the connection between geometries that they have learned from level 1 and objects in their life.

The last one is social interaction. Children can play the game with their peers in the collaborative mode which will enhance the social interaction. Also, they can get guidance and learn from older peers if they play the game together.

Executive function skill. Inhibitory control (IC) refers to a child's ability to suppress impulsive thoughts or behaviors and resist distractions and temptations (Obradović et al., 2012, p. 325). Although 2-year-olds can successfully delay or withhold some prepotent responses, the ability to exercise IC according to complex rules emerges toward the end of the third year of life and develops rapidly in preschoolers (Garon et al., 2008). For children aged between 6 to 8, they already master the basic of inhibitory control so that it's suitable to put it in our game. Inhibitory control is designed as the core elements of the collaborative mode. In this mode, each kid needs to focus on collecting objects similar to one specific shape and he cannot click on the shapes that belong to other people's tasks.

Digital representations. Within the context of human-computer interaction, an avatar is a perceptible digital representation whose behaviors reflect those executed, typically in real time, by a specific human being (Bainbridge, 2004). To help children more involved in the game, we design the avatar that can reflect children's execution. Cordova and Lepper found that children given more choices about their representation in a learning game environment exhibited more intrinsic motivation, more enjoyment, and more learning (Cordova & Lepper, 1996). That's why I design the avatar with customization options.

The avatar in a game is a Geometry Robot. Children can name the robot in their preferred ways and change its appearance according to what they like. Children can pick up different geometries that they have learned in level 1 and use it as a part of the robot's body. They can even change the size and color of each geometry. When a participant was offered a choice of avatar, in a sense gaining “ownership” of the avatar, arousal, presence, and identification were higher for third-person point-of-view games (games in which the player can see the avatar) than they were for first-person point-of-view games (Lim, 2006).

Level 3

In level 3, children need to use distributed geometries to make a composition the same as the one on the screen. It would be very difficult to operate since children need to navigate the space and connect different geometries together. To get children prepared with all the rules and help them get familiar with all the operations, I deploy some embodied agents together with the avatar.

An embodied agent, by contrast, is a perceptible digital representation whose behaviors reflect a computational algorithm designed to accomplish a specific goal or a set of goals (Bainbridge, 2004). Compared to avatars, the embodied agents control more mundane automatic behaviors. In level 3, each geometry has the ability to talk and give instructions. For example, one geometry can say “you can put a cylinder below me to complete the composition”. In this term, each geometry can be viewed as an embodied agent. There is a Central Geometry that will be fixed in space and requires the movement of other geometries to finish the composition. The Central Geometry will accompany with the user in all tasks while other geometries will only show up in specific tasks. Central geometry will act as a guide; it can answer and asks questions and helps the user when there is confusion. So we design the Central Geometry as the primary parasocial relationship while other geometries as the secondary parasocial relationships.

Parasocial relationships refer to one-sided, emotionally tinged relationships that people (in this discussion, children) develop with media characters (Calvert, Richards, Jordon, & Romer, 2014). Developing a child’s parasocial relationship with a character can make that character a powerful educational tool for that child (Brunick, Putnam, McGarry, Richards, & Calvert, 2016).

Future Work

There are still lots of areas that I can explore to make the design more reasonable and suitable for children's development. For example, I need to do more research on children's motor skills at different ages to make sure the design in level 3 is practical. Also, I would like to keep modifying my current design and add more details. Hopefully, I will try to develop it as my first real application.

References

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, *6*(4), 355–385.

Bacca, J., Baldiris, S., Fabregat, R., & Graf, S. (2014). Augmented reality trends in education: a systematic review of research and applications.

Bainbridge, W. S. (2004). *Berkshire encyclopedia of human-computer interaction* (Vol. 1). Berkshire Publishing Group LLC.

Black, J. E., & Greenough, W. T. (1986). Induction of pattern in neural structure by experience: Implications for cognitive development. *Advances in Developmental Psychology*, *4*, 1–50.

Brunick, K. L., Putnam, M. M., McGarry, L. E., Richards, M. N., & Calvert, S. L. (2016). Children's future parasocial relationships with media characters: the age of intelligent characters. *Journal of Children and Media*, *10*(2), 181–190.

Calvert, S. L., Richards, M. N., Jordon, A., & Romer, D. (2014). Children's parasocial relationships. *Media and the Well-Being of Children and Adolescents*, 187–200.

Cordova, D. I., & Lepper, M. R. (1996). Intrinsic motivation and the process of learning: Beneficial effects of contextualization, personalization, and choice. *Journal of Educational Psychology*, *88*(4), 715.

Diezmann, C. M., & Watters, J. J. (2000). Identifying and supporting spatial intelligence in young children. *Contemporary Issues in Early Childhood*, *1*(3), 299–313.

Dünser, A., Steinbügl, K., Kaufmann, H., & Glück, J. (2006). Virtual and augmented reality as spatial ability training tools. In *Proceedings of the 7th ACM SIGCHI New Zealand* *chapter's international conference on Computer-human interaction: design centered HCI* (pp. 125–132). ACM.

Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: a review using an integrative framework. *Psychological Bulletin*, *134*(1), 31.

Gelman, D. L. (2014). *Design for kids: digital products for playing and learning*. Rosenfeld Media.

Goswami, U., & Bryant, P. (2007). Children's cognitive development and learning.

Heckman, J. J. (2006). Skill formation and the economics of investing in disadvantaged children. *Science*, *312*(5782), 1900–1902.

Hirsh-Pasek, K., Zosh, J. M., Golinkoff, R. M., Gray, J. H., Robb, M. B., & Kaufman, J. (2015). Putting education in "educational" apps: Lessons from the science of learning. *Psychological Science in the Public Interest*, *16*(1), 3–34.

Jones, E. G. (2000). Cortical and subcortical contributions to activity-dependent plasticity in primate somatosensory cortex. *Annual Review of Neuroscience*, *23*(1), 1–37.

Kastens, K. A., & Ishikawa, T. (2006). Spatial thinking in the geosciences and cognitive sciences: A cross-disciplinary look at the intersection of the two fields. *SPECIAL PAPERS-GEOLOGICAL SOCIETY OF AMERICA*, *413*, 53.

Kaufmann, H., & Schmalstieg, D. (2002). Mathematics and geometry education with collaborative augmented reality. In *ACM SIGGRAPH 2002 conference abstracts and applications* (pp. 37–41). ACM.

Knudsen, E. I. (2004). Sensitive periods in the development of the brain and behavior. *Journal of Cognitive Neuroscience*, *16*(8), 1412–1425.

Lefevre, V., & Livet, N. (2012). Augmented reality method and devices using a real time automatic tracking of marker-free textured planar geometrical objects in a video stream.

Lim, S. (2006). *The effect of avatar choice and visual POV on game play experiences*. Stanford University.

Lohman, D. F. (1996). Spatial ability and g. *Human Abilities: Their Nature and Measurement*, *97*, 116.

National Scientific Council on the Developing Child. (2008). *The timing and quality of early experiences combine to shape brain architecture: Working paper No. 5*. Harvard University, Center on the Developing Child.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education*, *4*(3), 102–111.

Newport, E. L., Bavelier, D., & Neville, H. J. (2001). Critical thinking about critical periods: Perspectives on a critical period for language acquisition. *Language, Brain and Cognitive Development: Essays in Honor of Jacques Mehler*, 481–502.

Norman, D. (2013). *The design of everyday things: Revised and expanded edition*. Constellation.

Obradović, J., Portilla, X. A., & Boyce, W. T. (2012). Executive functioning and developmental neuroscience: Current progress and implications for early childhood education. *The Handbook of Early Education*, 324–351.

Rogoff, B. (1990). Cultural Similarities and Variations in Guided Participation. In *Apprenticeship in thinking: Cognitive development in social context* (pp. 111–134). New York, NY, US: Oxford University Press.

Uttal, D. H., Miller, D. I., & Newcombe, N. S. (2013). Exploring and enhancing spatial thinking: Links to achievement in science, technology, engineering, and mathematics? *Current Directions in Psychological Science*, *22*(5), 367–373.