Using Developmental Psychology to Guide Augmented-Reality Design for Children

Iulian Radu *
Georgia Institute of Technology

Blair MacIntyre
Georgia Institute of Technology

ABSTRACT

Augmented reality designers have great potential to enrich children's lives through AR experiences in education and entertainment. A significant difficulty in designing for children is that tremendous physical and cognitive development occurs across the first 10 years of life, and the changes in children's capabilities and limitations impact how these users respond to AR designs. Currently, little is known about how developmental changes relate to AR designs, or what AR designs are effective for young children. In this work, we focus on children 6-9 years old, presenting several concepts from developmental psychology and discussing how these relate to AR designs. Specifically, we investigate children's skills in the categories of motor abilities, spatial cognition, attention, logic and memory, and we discuss the relationship of these skills to current and hypothetical AR designs. Through this work, we intend to strengthen the field's understanding of AR usability and design, resulting in the generation of effective AR experiences for young users.

Keywords: Augmented Reality, Children, Psychology, Interaction Design, Mixed Reality.

Index Terms: H.5.1 [INFORMATION INTERFACES AND PRESENTATION (e.g., HCI)]: Multimedia Information Systems — Artificial, augmented, and virtual realities; K.8.0 [PERSONAL COMPUTING]: General- Games.

1. INTRODUCTION

There are many potential benefits which augmented reality (AR) technology can bring to children's lives, such as enhanced entertainment through whole-body interaction [1, 2], advancing education through in-situ interactive visualizations [3, 4], improving rehabilitation and skill development through physical manipulation [5, 6], etc. To achieve these benefits, augmented reality experiences need to be appropriately designed for children's capabilities and limitations. Presently, in the augmented reality design community there is a lack of systematic understanding of how to design AR experiences for children. This problem exists because children's augmented reality is a relatively new field, and the amount of applications is insufficient to generate design guidelines. In light of this issue, we present a framework for using developmental psychology knowledge in order to understand the space of AR design for children.

Developmental psychology tells us that children have certain capabilities and limitations, which are different than adults. Consequently, children will find some augmented reality designs as easy to use, and some as difficult, depending on children's developmental abilities. We focus on literature of motor and cognitive development, in order to identify several constructs useful as "lenses" for analyzing AR designs. We are interested in designing for children 6-9 years old, and focus on constructs directly related to children's abilities that are underdeveloped during this age range.

Understanding of how children's abilities relate to AR designs decision can help technology designers in several ways. First, this knowledge can be useful to identify designs that may lead to usability issues because they require children to use undeveloped abilities. Second, this knowledge can help to generate designs that challenge, train or educate children, by explicitly using or bypassing undeveloped abilities. Finally, this knowledge can help designers to determine the reasons for children's difficulties with existing designs, and to generate modifications to match children's abilities

The paper is structured as follows. Section 2 discusses related work involving the use of developmental theories in technology design. Section 3 presents augmented reality technology, and identifies various children's abilities relevant to augmented reality design. Sections 4-7 describe each ability and its influence on augmented reality designs. Section 8 discusses limitations and future work, and Section 9 concludes the paper.

2. RELATED WORK

Researchers have stressed the importance of considering developmental abilities when designing technology for children [7, 8], and several have argued explicitly for the use of psychological theories in informing technology design [8-10].

Baumgarten [9] describes aspects of physical, cognitive and psychosocial abilities of children 2-14 years old, and generates guidelines for the design of web-based applications for such children. In our work, we consider the domains of physical and cognitive abilities as applied to children 6-9 years old, considering more specific physical and cognitive skills, and relating these to the domain of augmented reality technology.

Gelderblom and Kotze [10] use psychological theories to generate a set of guidelines for desktop software design. The authors focus on children 5-8 years old, and look at theories of Piaget, Vygotsky, Case and Fischer. The generated guidelines account for children's cultural context, their emotional development, and abstract thinking skills. The guidelines are aimed at educational software, and indicate how designers may support as well as enhance children's skills. Most of the guidelines are applicable for general software design, and can be used for AR application design. Our present work differs by considering a subset of abstract thinking skills, while covering other abilities such as motor, spatial and attention skills. We are interested in software design more specifically for AR applications, and we do not generate explicit guidelines from our work.

* iulian@cc.gatech.edu

Bekker and Antle [11] present Developmentally Situated Design cards, a tool for making developmental psychology knowledge accessible to technology designers. The cards may be used at various points in the design process, and they provide description and examples of the abilities of children aged 5-12, in the domains of physical, cognitive, emotional and social skills. In our work, we do not consider the emotional and social skills, but we provide more depth for a subset of the physical and cognitive skills identified in the cards, and illustrate how these can be used by augmented reality designers.

In the domain of human-computer interaction, design guidelines and heuristics have been proposed [12, 13]. These are typically generally applicable to a range of computer applications, and are not specifically designed to account for children's developing skills.

In the augmented reality field, presently there are no general guidelines for designing applications for children. Recent research [14] has began to identify design patterns present in AR games, as well as the potential psychological principles underlying those patterns. The design patterns research differs from our present work in the level of abstraction of both the patterns and the psychological constructs. Design patterns identify issues related to experience design, while our work is mostly focused on in issues of interaction design. The psychological issues identified in the design patterns research are general concepts such as body awareness/skills, environmental awareness/skills, and social awareness/skills. Our present work identifies more specific constructs such as fine motor skills, hand-eye coordination, spatial memory, divided attention, etc. Furthermore, our work specifically focuses on child users and takes a theory-driven approach to analyzing the space of AR designs.

3. AUGMENTED REALITY AND CHILD ABILITIES

Augmented reality technology brings virtual entities into a child's physical world, and allows the child to interact with the virtual objects through direct, tangible interaction. Augmented reality can be experienced through a variety of technical setups, ranging between being desktop-based webcams (Figure 1), handheld phones (Figure 2), and head-mounted displays (Figure 4). In all configurations, physical objects are tracked, and augmented with computer graphics before being shown on the digital display.

Figure 1: The system from Hornecker and Dünser [15], showing a typical webcam-based augmented reality setup.

In this paper, we will focus mostly on handheld and webcam setups, because these have relatively low setup-costs and have the most potential for widespread use. A webcam-AR setup typically involves a fixed camera that is pointed at the user or at a table surface, and a computer display on which the augmented camera view is shown. Figure 1 shows the webcam-AR setup application from [15]. Handheld-AR typically involves a camera-enabled smartphone that the user is free to move using their hands. Figure 2 illustrates a typical handheld-AR system from [16]. In both these examples, the system typically tracks 2-dimensional images, in the form of cards or paddles, which the user manipulates in order to interact with the virtual world.

Based on developmental psychology literature, we believe that four general categories of developmental abilities are required when children interact with AR experiences. The categories are motor abilities, spatial abilities, attention abilities, memory and logic abilities. We believe that skills related to motor manipulation and spatial cognition have a major influence on children's experiences, since typical AR experiences augment 3D space and require interaction through physical movement. Additionally, we believe other skills such as attention, memory and logic can play an important role in children's experience of AR designs. A summary of the abilities is presented below.

Motor Abilities involve performing movements by using muscles and the human nervous system. Whenever children move their body across a large room, or move their hands to interact with an object, they make use of motor skills. Several motor abilities come into play depending on the complexity of the interaction. We will discuss the following motor abilities:

- ***Fine Motor Skills***: relate to children's abilities of performing precise movements
- ***Hand Eye Coordination***: relates to children's ability to adjust hand movements depending on what is visually perceived
- ***Multi-Hand Coordination***: involves the ability of moving both hands at the same time
- ***Gross Motor Skills and Endurance***: relate to the ability of performing large-scale movements, typically with the whole body, and children's ability to sustain prolonged postures or repeated movements

Spatial Abilities involve abilities for understanding and mentally visualizing spaces. We discuss children's abilities of:

- ***Spatial Perception***: the ability to understand objects and relationships in visually-observed space
- ***Spatial Memory***: the ability to remember objects and spatial relationships
- ***Spatial Visualization***: the ability to mentally imagine and transform space, such as mentally rotating objects or the viewing perspective

Attention Abilities relate to the child's capabilities of paying attention to items and activities. Depending on the interaction design, a child may be required to pay attention to multiple items or switch their attention between aspects of the experience. We identify the following related abilities:

- ***Divided Attention***: the ability to pay attention to multiple items/activities at same time
- ***Selective and Executive Attention***: the ability to control one's attention by focusing on a specific item while ignoring others (selective attention), or to switch out of an activity when needed (executive attention)

Logic and Memory abilities relate to the child's working memory abilities, as well as their abilities to think abstractly. The abilities covered will be:

- ***Memory Capability & Reversal***: the ability to remember items / actions, and recall them in reverse order
- ***Abstract over Concrete Thinking***: the ability to think about topics beyond what is concretely perceived

We believe these are the most pervasive abilities that are required when children experience AR applications. In the following discussion, we will provide examples of AR designs that can challenge each of these abilities. Table 1 presents a summary of typical AR designs that are problematic for these abilities.

Skill Type	Challenging AR interaction
MOTOR ABILITIES	
Multiple hand coordination	Holding a phone in one hand, and using other hand to move marker
Hand-eye coordination	Using a marker to intercept a moving virtual object
Fine motor skills	Moving a marker on a specified path
Gross motor skills & Endurance	Turning body around to look at virtual panorama Standing bent on a table, while playing handheld tabletop games
SPATIAL ABILITIES	
Spatial memory	Remember the configuration of a large virtual space, while using a handheld screen to see a limited view
Spatial perception	Understanding when a virtual item is on top of a physical item
Spatial visualization	Predict what virtual objects are visible by other people or virtual characters
ATTENTION ABILITIES	
Divided attention	Playing an AR game, and making sure to keep marker in view so tracking is not lost
Selective & executive attention	Playing an AR game while moving outdoors
LOGIC & MEMORY	
Remembering & reversing	Remembering how to recover from tracking loss
Abstract over concrete thinking	Understand that virtual objects are computer generated, and they do not need to obey physical laws

Table 1. Developmental skills and potentially challenging AR designs.

We will tend to look at each of these abilities from the perspective of four levels of design considerations: the technology setup (eg: Does handheld-AR pose more strain on some abilities?), by the space configuration (eg: Does the scale of the interaction space tax some abilities?), by the interaction design (eg: Do the types of interaction gestures pose a challenge?), and by the high level game design (eg: Are difficulties created by the style of game?).

4. Motor Skills

Augmented reality experiences are tied to physical spaces and physical objects, and users are typically expected to use physical movements as inputs to the experience. The following section will cover the skills of multiple hand coordination, hand-eye coordination, fine motor skills, gross motor skills, and endurance.

4.1 Multiple Hand Coordination

4.1.1 Description

Some physical activities require the use of two hands, and may even require coordination between hand movements. Examples of real-life bimanual coordination tasks are tying shoelaces, using a knife and fork to slice food, and making play-dough shapes. According to motor development research [17, 18], children have trouble performing actions with two hands, until reaching adult levels around 9 years old.

4.1.2 Considerations for AR

The AR technical setup influences the number of hands which can be used in an AR application. In webcam-based applications, children typically are free to perform activities using both hands, such as in the wIzQubes system [19] (Figure 5) where children touch two cubes to trigger an action.

In a handheld-based setup, children are typically required hold the AR device. In our observations, we noticed that children aged 6-7 usually hold the device with two hands, while older children are able to use one hand, leaving one hand free for gestural interaction. In the PuppyPlus game [20] (Figure 2), where children must move physical objects while watching the virtual world, it was observed that a 6 year old child would typically hold the phone with two hands, and would put the phone down when required to move physical pieces.

For our discussion, we classify two-hand coordination motions into three groups of increasing difficulty: interactions where both hands are performing the same motion, interactions where one hand is relatively stationary while the other moves, and interactions where both hands are performing independent motions.

Games such as the Nintendo 3DS cards game [21] fall into the first group. In this and similar handheld applications, the child holds the device with both hands, and aims by rotating or moving the closer/farther from the marker. In this kind of interaction, the movement in both hands is coupled together by holding the device, requiring a low amount of coordination between hands. We have observed that children as young as 6 can perform such actions.

The skill becomes more complex in handheld-AR applications requiring the child to hold the mobile device with one hand and perform an action with the other hand. For example, in the game of Invizimals [22], a game aimed at children in late childhood, children must use one hand hold the device aimed at a marker monster trap, and use the other hand to cover the trap when the monster walks in. As mentioned above, we tested a similar interaction with the educational handheld-AR game PuppyPlus [20] (Figure 2), and observed that at age 6 this kind of interaction appears difficult.

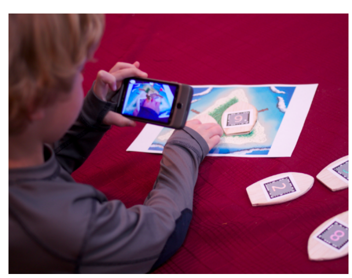

Figure 2: The PuppyPlus game from [23], a typical handheld-AR setup in which children use two hands for interaction.

Some AR designs may require both hands to perform independent motions. For example, in the Magic Story Cube application presented in [24], users must unfold a cube using both hands. There was no evaluation performed on this system, thus we cannot determine children's reactions. In the game of

Battleboard3D [25], actions are triggered when LEGO game pieces are broken apart and connected together. The game was tested with children 13 years old, and they indicated that the interaction disturbed the flow of the game, and that it also adds suspense. In the current children's AR literature, we do not find other applications requiring two-handed interaction.

The scale of the AR interaction space potentially adds complexity to the hand movements. We expect that two-handed gestures on 2D surfaces (eg: moving two cubes together, such as in wIzQubes [19]) are easier to perform than two-handed gestures in 3D space (eg: using two paddles to scoop).

We imagine that a variety of AR games can be built to train motor coordination skills, by challenging children to move both hands at the same time. Hypothetically, many two-handed gestures are possible to implement in AR systems, such as requiring children to use two hands to scoop up virtual items (eg: a fishing game), moving two items at the same time (eg: catching butterflies with two nets), or performing complex gestures (eg: drawing circles with both hands to spin a car's wheels).

4.2 Hand Eye Coordination

4.2.1 Description

Hand eye coordination involves adjusting hand movements according to real-time visual observation, such as when catching a ball, hitting a moving object, drawing, or gluing crafts. Until late childhood, children have trouble with hand-eye coordination tasks requiring object interception, because they have difficulties tracking objects, predicting positions of moving objects, and precisely coordinating their body's movements [26].

4.2.2 Considerations for AR

AR interactions always involve hand-eye coordination, as the user adapts their motions while watching the AR display. In this section, we will focus only on AR interactions that are significantly demanding for hand-eye coordination.

The degree of hand-eye coordination is determined in part by high-level design of the AR experience. Hand-eye coordination is strained when the user must perform lengthy and precise motion, such as moving a hand along a precise path, perform a complicated gesture such as drawing a symbol in the air, follow a moving object, etc. Interactions where the user must intercept moving objects also make use of hand-eye coordination skills. In the webcam-AR games of Wild Kratts [27] and EyePet [28], children must reach their hand to touch moving virtual animals. In these games, fine precision is not required, and our observations show that children as young as 6 years are excited to perform such motions in front of a screen.

The technology setup can add additional challenges for hand-eye coordination. A webcam AR system can be set up such that physical motions are not directly mapped to screen motions – for instance, if the camera rotated at an angle or if the image is mirrored; in this case, the user's forward motion will not correspond to an upward motion on the screen (typical of a mouse motion), thus requiring real-time adjustment of motions. In [15] (Figure 1), the authors present a webcam-based application where children's forward motions were mapped to downward motions on the screen. During their evaluation, children 6-7 years old were reported to have difficulty performing movements in this setup.

The challenge of hand-eye coordination skills can be intensified by requiring users to contain their motions to within a precise area and/or to perform motions within time constraints, such as a game which requires the child to move a racecar with his hand along a quickly-changing track. Furthermore, hand-eye coordination can be challenged through interactions where the user's motions are mapped in an indirect manner, for instance when an upward motion causes an object to move sideways.

4.3 Fine Motor Skills

4.3.1 Description

Fine motor skills involve performing of small-scale, precise muscle movements, such as writing, grasping an object, building a castle out of blocks, or eating with a fork. These motions require a developed nervous system, and are usually performed through precise control of fingers and forearm muscles. Research shows that children under 9-10 years old perform beneath adult level for fine motor skills: they will take more time to perform precise movements, and they have higher error rates. [17, 29]

4.3.2 Considerations for AR

The high-level design of the AR experience influences the level of fine motor skill required from its users. The skill becomes strained when children must move precisely within small areas, and when actions need to be performed under time constrains.

Most interactive AR applications use the technique of action "hotspots". In these applications, an action is triggered when the user touches a specific location, with either their hand or an AR marker. For example, [30] presents a webcam-based application designed for 3-5 year olds, where children must place animal cards on rectangular locations on a physical board. Once a card is placed in the correct spot, the system indicates whether the child correctly matched the animal with its environment. Similarly, in EyePet [28] (Figure 3), users move their hand to a virtual animal to make it react. When interacting with these systems, children need to have some degree of fine motor skills in order to move their hand to the precise locations in the AR world. With such interactions, it is expected that younger children will have more difficulty reaching hotspots, than compared to older children.

Some AR systems require precision through other types of movements, which are also challenging for children. In the example of the AR Spot system presented in [31], children 8-12 can tilt marker cards to specific angles in order to cause virtual objects to fall. Other systems can trigger actions based on distance between two items: characters in the game of Nerdferno [32] respond when the user's device is close to them. Another type of precise movement is the use of the whole body for aiming – in the Nintendo 3DS cards game [21], the user aims at virtual objects by moving and rotating the handheld device. In all these systems, the interaction relies on the child's ability to perform precise movements using their hands or whole upper body. In the AR literature we could not find reports of evaluations of these kinds of interactions with children, but we expect that they are more challenging than the hotspot-based interactions presented above.

The spatiality of the AR experience is likely a factor influencing the degree of fine motor skill involved. Applications where the user interacts on a 2D surface will be less demanding than those requiring precise interaction in 3D space. Most AR applications for children restrain interactions to a 2D planar space, typically performed on a table surface. Some handheld AR applications exist which rely on 3D interactions through full-body movement, such as aiming with a handheld device (eg: [21]).

From a technological point of view, precision and speed are bounded by the camera resolution, camera capture speed, and the quality of the tracking algorithms. The technology available to most AR end-users is in the form of webcams and smartphone cameras, which have a fairly low framerate, resulting that users cannot precisely perform quick gestures such as swiping or shaking. Further, due to low resolution of the camera and quality of popular tracking algorithms, object locations cannot be precisely determined especially when far from the camera. These factors limit the precision and speed of interactions possible in AR applications.

Figure 3. In Sony's EyePet game [28] (top), children must employ hand-eye coordination to touch the moving virtual pet with their hand. In Art of Defense [33] (bottom row), fine motor skills must be used for drawing and manipulating game pieces.

AR applications can be designed to train children's fine motor skills by requiring children to perform precise movements with their hands. AR applications can track locations and rotations of AR markers, and can thus require children to perform precise joint movements, such as in a game where the child must mix colors by precisely turning virtual buckets; or, to perform precise movements, such as moving a virtual magic wand along a path in order to cast a spell.

4.4 Gross Motor Skills & Endurance

4.4.1 Description

Gross motor skills involve large muscle movements, such as when jumping, walking, bending the body in a certain shape, or using the hand to point in a direction. These skills are usually developed by 6 years old [26], but should be considered for technology designers since skill proficiency can impact children's performance.

In this section we will also consider the fact that some postures and movements are difficult to perform for extended periods of time. For instance the following activities will cause bodily pain after prolonged period of time: holding a hand outstretched, playing while bent on the floor, repeatedly moving a hand between two places. Children have lower endurance for muscle strain, and ergonomically-problematic postures should be avoided to avoid bodily harm.

4.4.2 Considerations for AR

The type of technology used in the AR system will have a large impact on the type of gross motor skills involved. With webcam-based AR, the camera can be pointed toward the user's surrounding room, and the system may detect gross motor movements such as the child jumping, crouching, or creating various shapes by bending limbs [34]. In handheld-AR setups, the user can be restricted to interact on a table surface, or be free to move around a space as large as a whole city. In both cases, the user can be expected to employ gross motor skills in rotating their body, moving closer/far from virtual objects, walking and potentially running. Children as young as 6 are able to play with handheld games such as Eyepet for PSP [28] that requires bending and turning the body.

Regarding endurance, requiring children to hold a posture for a long time is problematic. AR games played on table surfaces should not require children to stand up with their back bent - our observations with 6-8 year old children indicate that after roughly 5 minutes of sustained posture, children's muscles being to hurt. Games where children must hold their arms up will become straining, such as games where must hold phone to look around [22], or games where children must wave their hands [27]. In observations of 6-8 year old children playing the Wild Kratts game [27], children frequently reported hand tiredness. Games where users perform repeated movements even on a table surface are reported as straining after 10 minutes [35].

5. SPATIAL SKILLS

Augmented reality is inherently a spatial experience, as it enables users to interact in environments that are mixtures of virtual spaces and real spaces, thus spatial cognition are frequently employed. The following section will cover spatial memory, spatial perception, and spatial visualization abilities.

5.1 Spatial memory

5.1.1 Description

Spatial memory is the ability to remember the configuration of objects in space, for instance remembering important places in a neighborhood, the configuration of a chessboard, or the configuration of atoms in a chemical structure. Children have difficulty accurately remembering spaces: they can remember a limited number of items, and some researchers believe that before 6 years old children remember object relationships in topological, not Euclidean terms (ie: they remember order of items, not distances) [36].

5.1.2 Considerations for AR

The AR technological setup can influence requirements on spatial memory. Handheld devices offer a small window into a virtual scene, and when users zoom into specific parts of the virtual scene, they lose track of virtual objects beyond the view of their device. For instance, in the game of Nerdferno [32], users are forced to get close to virtual characters, and direct them around a virtual maze. This interaction is challenging because the user must either remember the spatial layout of the game, or to frequently pull back to reorient themselves. No experiments have been performed to determine children's performance on such AR applications. On the other hand, webcam-based AR applications typically do not tax spatial memory in this way, since the virtual world is typically fully visible from the camera view.

At the interaction level, certain AR designs can challenge user's spatial memory. There exist several AR games where the faces of physical cubes are mapped to virtual spaces. For example in wIzQubes [19], two cubes are used – on one cube, each face represents a tool, while on the other cube, each face represents a virtual world. At various stages in the game, children are required to show the appropriate cube face for the task at hand. In formal testing we have observed that children 6-8 have problems remembering which face corresponds to which item, and have problems remembering relationships between the faces. The game of Levelhead [37] uses a similar interaction design, where a cube's faces are mapped to virtual spaces that must be traversed by a virtual character. The game is challenging because the user must identify and remember how these spaces are related. To our knowledge, it has not been evaluated with children.

Finally, the high-level aim of the AR experience contributes to the degree of spatial memory. Games intended for teaching spatially distribution of objects will undoubtedly require and potentially improve students' use of spatial memory. The application in [38], presents children 7-13 years old with the configuration of organs in the human body. In comparing this system with a traditional book, it was found that children learned more with the AR condition.

Spatial memory may be trained through AR applications which allow children to visualize complex spaces, as the example in [38] shows, and also through games where students must remember physical locations. The AR experience can require children to remember locations and relationships of virtual objects, for example, a large-scale Memory game requiring collection of items distributed in a large physical space, or, a game where users must stay away from certain locations. We are not aware of evaluations of spatial performance in large-scale AR games.

5.2 Spatial perception

5.2.1 Description

Spatial perception refers to the ability of understanding 2D or 3D spaces, including understanding object positions, sizes and relationships between objects. It is used in tasks such as estimating the nearest player on a playing field, or understanding relative distances between planets in an astronomy model. Young children are able to identify objects and their relative sizes, but have trouble estimating distances [36].

5.2.2 Considerations for AR

When interacting with augmented reality, the AR space is always perceived through a display which mixes virtual graphics with a camera-captured image, thus the properties of the display technology affects children's spatial perception. Small displays, or displays with low resolution, will make objects and relationships difficult to see. Similarly, the resolution and image quality of the camera device will determine how clearly the physical world is seen.

Children interacting with an AR experience need to perceive both physical and virtual objects, as well as the relationships between them. The quality of the virtual graphics, and the integration of virtual graphics with physical content, will further influence the perception of objects and relationships: in typical AR applications, virtual graphics are overlaid on the camera image, thus virtual objects always appear in the foreground and are not occluded by physical objects such as the user's hands. This fact, along with the artificial appearance of virtual graphics, makes it difficult to judge virtual objects' positions in the physical space. There are ways to aid a user's spatial perception of virtual objects, such as by using depth cues, realistic textures, shadows, accounting for environmental lighting, and using other methods of photorealistic rendering [39].

Spatial perception is important in applications where the user must understand how virtual information is aligned to physical locations. In educational applications like the Wikitude tour guide [40] and the magnetic field visualization app in [41] (Figure 6), the user must understand that the virtual objects represent information about the physical object to which they are spatially near. Spatial perception is also employed when users must understand and reason about configurations of virtual structures, such as in educational applications showing astronomy [4] or chemistry [42].

Typically, AR applications for children do not require interaction with complex spatial configurations. Advanced spatial perception abilities will come into play in future applications where users must physically interact with virtual objects that "float" in 3D space. In such cases, the user must estimate how the virtual object ties to the physical world, so that he can appropriately move their hand to touch the object. There are no examples for young children, although the high-school physics system of Kaufmann [43] makes use of interaction with such floating objects.

Figure 4. Spatial cognition skills are required for understanding and interacting with the system such as PhysicsPlayground [43].

5.3 Spatial visualization

5.3.1 Description

Spatial visualization abilities involve mentally visualizing and modifying spatial configurations. This involves rotating objects in one's mind, such as imagining how a puzzle piece fits into a larger puzzle, or imagining how a space looks from different perspectives. Visualization also involves estimating how moving an object will reconfigure a space, for instance determining what piece to remove from a structure without toppling the structure, or understanding where a moving projectile will land. Children's mental visualization abilities develop until late childhood. Before about 8 years old, children have trouble estimating what another person sees, and they may have trouble with mental rotations [36].

5.3.2 Considerations for AR

The spatial visualization ability is required in applications where the user must imagine reconfigurations of virtual or physical objects. For example, in the Playstation Vita game of PulsAR [44], the user must physically move virtual mirrors in order to direct a laser beam to a destination. To our knowledge, this game has not been tested with young children, and no other AR applications exist where children must mentally visualize reconfigurations of space as part of strategizing their gameplay.

The visualization ability also is required in applications where the user needs to change perspective in order to solve tasks. For example in the Nintendo 3DS card game [21], the user must move to different sides of the playing board in order to shoot at targets. If the user wishes to avoid unnecessary movement, they must mentally visualize which angle is the best for shooting the target. Perspective-taking also comes into play in co-located multiplayer AR games, where players must imagine what other players are seeing from their physical perspective. In evaluating the multiplayer fishing game of Bragfish [45], the authors indicate that players used each other's physical locations to learn about fish populations at different locations in the virtual world.

Research on children's AR applications does not indicate whether young children can perform these sorts of visualization tasks.

AR applications can offload a user's spatial visualization skills: the AR system can visualize transformations of space, while the user performs epistemic actions to explore different spatial configurations. For example, the Refurbish 3D system [46] is constructed to show how furniture will look in a user's home. The user can easily reconfigure the space and immediately view it on the screen. In such systems, the user does not need to perform any mental visualization operations. In order to force users to employ mental visualization skills, the AR activity can add constraints on the activity, for instance requiring children to achieve a certain spatial configuration within a certain amount of time, or within a certain amount of moves.

6. ATTENTION SKILLS

Attention is a basic skill required in any kind of game, and augmented reality users need to control the focus of their attention as they interact with the experience through the technology interface. The following section will discuss divided attention, selective attention and executive attention abilities.

6.1 Divided Attention

6.1.1 Description

Divided attention tasks involve attending to multiple items at the same time, such as involved in doing homework while watching TV, riding a bike while talking to a friend, or listening to two conversations at once. Until about 8 years old, children can only focus on one item / activity at a time [11, 36].

6.1.2 Considerations for AR

The technology used in the AR experience can require children to divide their attention. In webcam-based AR (Figures 1 and 5) where a webcam views a table surface, children's physical actions must occur in one "input" space (ie: on the table surface), while they observe the AR view in another "output" space (ie: on the computer monitor). It is likely that this task requires some degree of divided attention. Although this interaction is similar to using a computer mouse, where the input and output spaces are different, it may require significantly more attention for several reasons: the child sees the real world in two places, the child performs gestures in 3D space, and the input and output spaces may be indirectly coupled (as mentioned in Section 4.2). In [15], children 6-7 years old were reported to have problems moving objects in the webcam-AR setup, and divided attention may have contributed to this problem.

For handheld AR, and other cases where the user is free to control the camera, divided attention comes in another form: the user must divide their attention between attending to the AR application, as well as to ensuring that the camera movements do not cause tracking loss (which typically occurs when the camera is moved away or too close to the tracking surface). Because of these constraints, the users must keep attention on the technology while playing the game, a task that seems difficult for young children. In studies of 6-8 year old children playing AR games, we observed that children became fully focused on the game, leading to frequent occurrences of tracking loss. This effect can be ameliorated by designing games in such a way that users are discouraged from leaving the playing area, for instance by penalizing users from moving away from the playing area.

Another case where divided attention comes into play is when virtual content occludes a user's physical actions. This is typically the case in AR applications for object assembly [6]. In these contexts, the user may need to divide his attention between performing physical actions behind the occlusion, and observing the virtual content in response to his actions.

Figure 5. Interacting with the wIzQubes system [19] may require children to guide attention between activities of physical manipulation, gameplay and social interactions.

Using instructions in games may also cause problems due to children's inability to divide attention between observing the game and attending to the instructions. Hornecker et al [47] report that some children did not respond to spoken instructions while interacting with the AR content. This may be because the AR was so captivating that children were unable to focus on the instructions.

Finally, the high-level design of a game can be designed to challenge children's divided attention, by explicitly requiring children to attend to multiple game items at the same time, for instance in a game of virtual Breakout where children must attend to two balls at the same time.

6.2 Selective & Executive Attention

6.2.1 Description

Some activities require children to have skillful control of their attention, such as listening to a conversation in a noisy room, following a ball in a busy sports game, or switching attention between playing a game and observing the time. These examples illustrate children's abilities to focus on a specific item/activity while ignoring others (selective attention), and to consciously switch attention between items/activities (executive attention). Research indicates that children have trouble controlling their attention: at times children can become very focused on one aspect of an activity while ignoring external stimuli, while at other times they can have trouble focusing on the activity, being easily distracted [36].

6.2.2 Considerations for AR

Executive attention is required when the user must switch their attentional focus out of the gameplay, such as in cases where AR games are played outdoors. In these cases, the user must actively stop playing and attend to their environment in order to avoid physical obstacles. In a GPS-based outdoor game for high school children, [48], children were observed to be fully captivated by the game while they walked in public spaces. We have found no handheld-AR applications for children which requires users to walk around while playing, but we expect this will be a recurring problem, since young children can be very focused on the game activity, and since the AR view may mislead users to think that they are actually paying attention to the real world.

Selective attention is explicitly required when the AR experience occurs in an active or noisy environment, such as in a school hallway, a playground, a museum, etc. In these cases, the user must ignore external stimulation in order to engage with the AR experience.

AR designs involving occlusion can lead to interaction problems due to children's undeveloped abilities to control their attention. Children may be expected to perform complicated physical actions while their hands are occluded, such as in the system presented in [49]. The authors report that 8-10 year old children had difficulties operating zippers while their hands were occluded by virtual content. In such cases where complex physical actions are required, children can benefit from ignoring the AR view and explicitly focusing their attention on physical movements; however, such attentional control may be difficult.

Control of attention is also required when children deal with multiplayer co-located AR games. In such cases, a useful strategy is to stop paying attention to one's own gameplay, and instead observe the actions of the other players – such as analyzing another player's physical location in relation to the game world, or listening to the sounds of their mobile device. In the evaluation of Bragfish [45], players reported stopping their gameplay to observe other players. Designers intending to have players observe and respond to each other's physical presence, must design games in such a way that children do not have to intensely attend to their own device.

7. LOGIC AND MEMORY SKILLS

Like attention, abilities related to logic and memory enter into play in variety of games. We will consider skills related to memory capacity and reversal, as well as the ability to think about abstract concepts.

7.1 Memory capacity & reversal

7.1.1 Description

Working memory is the mechanism for holding pieces of information in mind while performing a task. In children's lives, this skill becomes employed when children must remember the rules of a game or remember a shopping list. While adults can hold roughly seven items in working memory, children younger than 11 years old have a more limited capacity (eg: by 6 years old, they can remember only four items) [36]. This impacts children's ability to recall instructions or previous actions. Additionally, some tasks require children to not only remember a sequence of items / actions, but also to reverse this sequence: for instance deducing how to take apart a toy, or navigating menu hierarchies. Until about 8 years old, children have trouble reversing items in memory [36].

7.1.2 Considerations for AR

The AR technology setup can pose requirements for remembering and reversing activities. In handheld-AR applications, tracking will be lost when the camera goes out of the view of the marker, and users of such must remember how to fix the system when this happens. In such cases is frequently useful to remember one's last action and reverse it in order to quickly regain tracking. In our observations of 6-8 year old children, we have noticed that 8-year old children were quick to recover from tracking-loss when no instructions were given, while 6 year olds had difficulties.

Memory reversal abilities may be challenged or trained through the high-level design of the AR application. An application may be designed such that users are forced to backtrack through items or actions. For instance, a game may require users to visit a set of physical locations in reverse, requiring users to make use of spatial memory as well as memory reversal; or, a game may require users to perform actions in reverse, such as taking apart recently-built structure. We know no children's AR games that require these sorts of interactions, but as AR games become more complex, expected that such things designs will appear.

Rules of play are a crucial part of games, and children must also remember these in order to have enjoyable play experiences. In AR applications, children also need to remember how to interact with the system. Although AR is a natural interface where children can typically use intuitive hand motions to directly touch virtual content, non-intuitive interactions can also be required. For example, in the game Art of Defense [33] (Figure 3 bottom), users need to draw geometric shapes to create virtual objects. In such games, users need to remember these special interactions. In other games, children muse use generic-looking physical objects for interaction, such as cubes labeled with abstract symbols such as in the wIzQubes system [19] (Figure 5), and children may need to remember the meanings of these symbols.

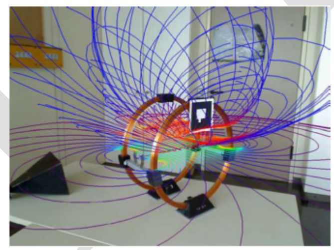

Figure 6. The system in [50] illustrates magnetic field lines around a physical object. Abstract thinking skills are required to understand what the virtual lines represent and how they relate to the physical space.

7.2 Abstract over Concrete Thinking

7.2.1 Description

Abstract thinking involves processing information about properties not concretely observed. For example, abstract thinking is used when understanding the concept of number, when observing a similarity between three triangles and three squares; or, when understanding that the amount of a body of water is not changed as the water moves between a tall and a short container. Generally, abstract thinking includes the ability to think about invisible aspects of a problem, reflect on one's previous actions, draw inferences, plan, create hypotheses, and think strategically. Between the ages of 7-11 years old, children are in Piaget's concrete operations stage, and begin to reason logically: they master the conservation task, begin to see problems and spaces from other people's point of view, and begin to think about strategies. However, logical induction and abstract thinking skills continue to develop past the end of this stage [36].

7.2.2 Considerations for AR

When interacting with an AR experience, it is sometimes beneficial for users to have an abstract understanding of the system, and to be aware that virtual objects are artificially-constructed. Virtual objects in AR applications may not be programmed to fully obey real-world physics, and this can be disconcerting to children who do not have an abstract understanding of computers. In the system presented in [47], children 6-7 years old expected virtual objects to respond to interactions suitable for physical objects, even after having learned proper techniques for interacting with such objects. In some applications, interactions with virtual objects may outright defy virtual laws, for instance tilting a virtual character may cause it to "fall" upwards, or to change its size [31]. In an AR experience, children need to conceptualize virtual entities in a different way than physical objects, and this may be difficult.

Understanding what virtual entities are meant to represent, also requires a form of abstract thinking. With AR, it is possible to give a physical shape to an abstract concept, for example representing the pollution in a city block as floating sphere, or representing a person's emotion as a cloud above their head. These objects may appear as if they exist in the world around the user, but users must understand that they are representations of abstract concepts. The topic of young children's understandings of representations of abstract concepts in AR is unexplored.

Conversely, sometimes the user may need to understand that virtual objects are actually representations of invisible information, such as when seeing magnetic field lines [41] (Figure 6). Such applications, where the AR gives physical representation to invisible concepts are great for education, but it requires thinking beyond the concrete. From the literature it is unclear how children conceptualize such AR experiences.

8. CONCLUSIONS, LIMITATIONS & FUTURE WORK

This paper has presented a set of children's developmental abilities that are employed in children's interaction with augmented reality technology. We have identified children's capabilities and limitations in the areas of motor skills, spatial cognition, attention, logic and memory, and we have discussed how these relate to various AR design considerations. We hope that by sensitizing designers to these constructs, we gain a better understanding of designing age-appropriate AR applications.

We have presented various motor and cognitive abilities of children, and illustrated how these can be required by different augmented reality designs. The space of AR designs for children is largely unexplored, however, and a significant amount of the claimed relationships between child abilities and AR designs are hypothetical. By presenting a broad set of guidelines supported by case studies and psychology theory, we are providing the foundation for follow up hypothesis-driven studies, and hope that further research will empirically clarify the implications of our framework.

We do not claim that the list of abilities identified in our work is comprehensive, and note that there are other developmental abilities not mentioned but potentially relevant to children's performance in AR experiences - abilities such as visual acuity, visual tracking, proprioception, or symbolic reasoning. Further research is necessary to determine how such skills relate to children's performance with AR designs.

Our work has also not specifically identified one-to-one relationships between developmental skills and AR designs. We have focused on individual skills because these are explicitly separated in the domain of psychology. However, it is expected that when a child interacts with any AR experience, many of the skills identified above will be invoked concurrently. Furthermore, skills may interact with each other (for example, fine motor skill performance is likely impacted by spatial perception acuity; or, abstract thinking skills may mediate attention control ability). One avenue for further research is the exploration of interrelationships between children's skills, and application of this knowledge to improving performance in AR (eg: improving fine motor skills by modifying the AR rendering quality). Another direction for future work involves studying the relationship between AR designs and specific developmental capabilities, potentially by researching correlations between child performance on specific AR tasks and standard psychological measures such as the Mental Rotations Test.

We also have not identified how children's age influences performance with different AR designs. The number of existing AR applications for children is too low for performing such fine-grained analysis at present. Further, psychologists and educators indicate that children's capabilities at specific ages are not uniform across all children of that age group, due to factors such as gender, socioeconomic level, experience with technology, and other non-biological factors [36]. However, since children's products are typically designed for narrow age segments, it is highly useful for AR designers to understand how to design for specific age groups; thus, it would be beneficial if future research investigates this direction.

Another limitation is that our analysis is based on a large number of AR games. This is because young children's applications are typically in the form of games, and most existing AR applications for children fall into this domain. The application domain, as well as the application's context of use, may influence how children apply their skills (eg: in a classroom context, children may be more attentive to an educational application, than compared to a home context). Future work could refine the guidelines to apply to specific application types and contexts of use.

Future work can also investigate the use of developmental psychology to create child-friendly AR designs that bypass problematic skills; or, to create applications that are challenging and/or educational because they challenge undeveloped skills.

Finally, the current framework is presented for designers of augmented reality technology. However, the skills identified above are potentially transferrable to other domains, such as tabletop interfaces and tangible user interfaces. Future work can investigate the applicability of the developmental concepts to other technologies.

9. ACKNOWLEDGEMENTS

We would like to thank Dr. Alissa Antle from Simon Fraser University and Dr. Stella Lourenco from Emory University, as well as the reviewers of our paper, for their thoughtful comments on the topic of this research.

10. REFERENCES

[1] R. De Lisi and J. L. Wolford, "Improving children's mental rotation accuracy with computer game playing.," *The Journal of genetic psychology,* vol. 163, pp. 272-82, 2002.

[2] M. Billinghurst, "Augmented reality in education," *New Horizons for Learning,* 2002.

[3] B. Shelton and N. Hedley, "Exploring a Cognitive Basis for Learning Spatial Relationships with Augmented Reality," in *Technology, Instruction, Cognition and Learning* vol. 1, ed, 2004, pp. 323 - 357.

[4] L. Kerawalla, R. Luckin, S. Seljeflot, and A. Woolard, ""Making it real": exploring the potential of augmented reality for teaching primary school science," *Virtual Reality,* vol. 10, pp. 163-174, 2006.

[5] A. S. Merians, D. Jack, R. Boian, M. Tremaine, G. C. Burdea, S. V. Adamovich, M. Recce, and H. Poizner, "Virtual reality–augmented rehabilitation for patients following stroke," *Physical therapy,* vol. 82, p. 898, 2002.

[6] A. Tang, C. Owen, F. Biocca, and W. Mou, "Comparative effectiveness of augmented reality in object assembly," *Proceedings*

of the conference on Human factors in computing systems - CHI '03, p. 73, 2003.

[7] A. Bruckman and A. Bandlow, "Human-computer interaction for kids," in *The human-computer interaction handbook*, 2002, pp. 428-440.

[8] P. Wyeth and H. C. Purchase, "Using developmental theories to inform the design of technology for children," in *Proceeding of the 2003 conference on Interaction design and children - IDC '03*, New York, New York, USA, 2003, p. 93.

[9] M. Baumgarten, "Kids and the internet: a developmental summary," *Computers in Entertainment (CIE),* vol. 1, p. 2, 2003.

[10] H. Gelderblom and P. Kotzé, "Designing technology for young children: what we can learn from theories of cognitive development," in *Proceedings of the 2008 annual research conference of the South African Institute of Computer Scientists and Information Technologists on IT research in developing countries: riding the wave of technology*, 2008, pp. 66-75.

[11] T. Bekker and A. N. Antle, "Developmentally situated design (DSD): making theoretical knowledge accessible to designers of children's technology," *Proceedings of the 2011 annual conference on Human factors in computing systems,* pp. 2531--2540, 2011.

[12] A. Dix, J. Finlay, G. Abowd, and R. Beale, *Human-computer interaction*, 2004.

[13] J. Nielsen, "Ten usability heuristics," *Useit. com,* 2005.

[14] Y. Xu, E. Barba, I. Radu, M. Gandy, B. Schrank, B. Macintyre, and T. Tseng, "Pre-Patterns for Designing Embodied Interactions in Handheld Augmented Reality Games," in *International Symposium on Mixed and Augmented Reality*, 2011.

[15] E. Hornecker and A. Dünser, "Supporting Early Literacy with Augmented Books–Experiences with an Exploratory Study," in *Proceedings of the German Society of Informatics Annual conference (GI-Jahrestagung) 2007*, 2007.

[16] I. Radu, E. Hanlon, Y. Xu, B. Gee, and W. Whittaker. *Puppy Plus*. Available: http://www.youtube.com/watch?v=ArUp1gxUrOU

[17] J. P. Hourcade, "Interaction design and children," *Foundations and Trends in Human-Computer Interaction,* vol. 1, pp. 277-392, 2008.

[18] J. Fagard, "The development of bimanual coordination," ed: Charleston, SC: University of South Carolina Press, 1990.

[19] Z. Y. Zhou, A. D. Cheok, J. Tedjokusumo, and G. S. Omer, "wIzQubesTM–A novel tangible interface for interactive storytelling in mixed reality," *Int J Virtual Real,* vol. 7, pp. 9-15, 2008.

[20] I. Radu, E. Hanlon, Y. Xu, B. Gee, and W. Whittaker, "Puppy Plus," in *Youtube*, ed, 2011.

[21] K. Stuart, "Nintendo 3DS hands-on report," ed, 2010.

[22] S. C. Entertainment, "Invizimals," ed, 2012.

[23] I. Radu, E. Hanlon, Y. Xu, B. Gee, and W. Whittaker, *Puppy Plus*, 2011.

[24] Z. Zhou, A. D. Cheok, J. Pan, and Y. Li, "Magic Story Cube : an Interactive Tangible Interface for Storytelling," *Computer,* pp. 3-4, 2004.

[25] T. L. Andersen, S. Kristensen, B. W. Nielsen, and K. Grønbæk, "Designing an augmented reality board game with children: the battleboard 3D experience," in *Proceedings of the 2004 conference on Interaction design and children: building a community*, 2004, pp. 137-138.

[26] D. L. Gallahue and J. C. Ozmun, *Understanding motor development: Infants, children, adolescents, adults*: McGraw-Hill New York, 1998.

[27] PBS KIDS. *Wild Kratts . Caracal Leap*. Available: http://pbskids.org/wildkratts/games/caracal-leap/

[28] Sony Computer Entertainment. *EyePet TM*. Available: http://www.eyepet.com/

[29] J. H. Yan, J. R. Thomas, G. E. Stelmach, and K. T. Thomas, "Developmental features of rapid aiming arm movements across the lifespan," *Journal of Motor Behavior,* vol. 32, pp. 121-140, 2000.

[30] P. Campos and S. Pessanha, "Designing Augmented Reality Tangible Interfaces for Kindergarten Children," *Virtual and Mixed Reality-New Trends,* pp. 12-19, 2011.

[31] I. Radu and B. MacIntyre, "Augmented-reality scratch: a children's authoring environment for augmented-reality experiences," in *Proceedings of the 8th International Conference on Interaction Design and Children*, Como, Italy, 2009, pp. 210-213.

[32] Georgia Institute of Technology. *Nerdferno*. Available: http://www.youtube.com/watch?v=TPaIsj56dJY

[33] D. N. T. Huynh, K. Raveendran, Y. Xu, K. Spreen, and B. MacIntyre, "Art of defense: a collaborative handheld augmented reality board game," in *Proceedings of the 2009 ACM SIGGRAPH Symposium on Video Games*, 2009, pp. 135-142.

[34] Microsoft Corporation. *Kinect*. Available: http://www.xbox.com/en-US/kinect

[35] A. G. D. Correa, G. A. de Assis, M. Nascimento, I. Ficheman, and R. D. Lopes, "Genvirtual: An augmented reality musical game for cognitive and motor rehabilitation," in *Virtual Rehabilitation, 2007*, 2007, pp. 1-6.

[36] R. A. Rosser, *Cognitive development: Psychological and biological perspectives*: Allyn and Bacon Boston, 1994.

[37] J. Oliver. *Levelhead*. Available: http://selectparks.net/~julian/levelhead/

[38] A. Nischelwitzer, F.-j. Lenz, G. Searle, and A. Holzinger, "Some Aspects of the Development of Low-Cost Augmented Reality Learning Environments as Examples for Future Interfaces in Technology Enhanced Learning," *Access,* pp. 728-737, 2007.

[39] S. Gibson, A. Chalmers, G. Simon, J. F. Vigueras-Gomez, M. O. Berger, D. Stricker, W. Kresse, and others, "Photorealistic augmented reality," in *Second IEEE and ACM International Symposium on Mixed and Augmented Reality-ISMAR*, 2003, p. 3.

[40] Wikitude. *Wikitude*. Available: http://www.wikitude.com/en/

[41] A. Buchau, W. M. Rucker, U. Wössner, and M. Becker, "Augmented reality in teaching of electrodynamics," *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering,* vol. 28, pp. 948-963, 2009.

[42] M. Fjeld and B. M. Voegtli, "Augmented chemistry: An interactive educational workbench," in *Mixed and Augmented Reality, 2002. ISMAR 2002. Proceedings. International Symposium on*, 2002, pp. 259-321.

[43] H. Kaufmann and B. Meyer, "Simulating Educational Physical Experiments in Augmented Reality," 2008.

[44] Sony Computer Entertainment. *Playstation Vita*. Available: http://us.playstation.com/psvita/

[45] Y. Xu, M. Gandy, S. Deen, B. Schrank, K. Spreen, M. Gorbsky, T. White, E. Barba, I. Radu, and J. Bolter, "BragFish: exploring physical and social interaction in co-located handheld augmented reality games," *Proceedings of the 2008 international Conference on Advances in Computer Entertainment Technology,* pp. 276-283, 2008.

[46] J. Koopferstock. *Refurnish in 3D: Constructive Tech Demo*. Available: http://www.enlighten3d.com/2008/12/17/refurnish-in-3d-constructive/

[47] E. Hornecker and A. Dünser, "Of pages and paddles: Children's expectations and mistaken interactions with physical–digital tools," *Interacting with Computers,* vol. 21, pp. 95-107, 2009.

[48] M. Dunleavy, C. Dede, and R. Mitchell, "Affordances and Limitations of Immersive Participatory Augmented Reality Simulations for Teaching and Learning," *Journal of Science Education and Technology,* vol. 18, pp. 7-22, 2008.

[49] C. Juan, F. Beatrice, and J. Cano, "An augmented reality system for learning the interior of the human body," in *Advanced Learning Technologies, 2008. ICALT'08. Eighth IEEE International Conference on*, 2008, pp. 186-188.

[50] A. Buchau, W. Rucker, U. Wossner, and M. Becker, "Augmented reality in teaching of electrodynamics," *Computation and Mathematics in Electrical and Electronic Engineering,* vol. 28, pp. 948-963, 2009.