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Digital games for spatial reasoning in the early years: Building the foundations for STEM learning

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CONTEXT

The importance of STEM knowledge and skills, today and into the future, is critical, and the urgency to address the current skill shortage and gender disparity is pressing. Spatial reasoning skills, the ability to visualise and manipulate objects and their environment in one's mind, have been shown to be foundational to mathematics skills; development of these from early childhood is critical to predisposing individuals for later success and interest in STEM fields, particularly Engineering. There are very few studies involving pre-school children in home settings, hence there is a gap in the understanding of the early experiences that contribute to their spatial learning, especially for girls.

PURPOSE

The purpose of this paper is to present three newly created digital resources, which will form part of a suite of resources in a study to understand how parents and caregivers can promote and support preschool children's visual spatial skills development in home settings.

APPROACH

The digital resources are built using combined principles from spatial reasoning literature, Vygotsky's cultural-historical conception of child development, and the Conceptual Playworlds model of play-based learning. We anticipate that this approach will lead to a take up of spatial games that evoke children's imagination and creativity, better engaging them and supporting the development of their visual spatial skills.

ACTUAL AND ANTICIPATED OUTCOMES

We have created three new apps: an Augmented Reality app that illustrates spatial relations, and two game apps to help familiarise children with mental rotation and shape recognition. We believe these apps will provide spatial learning affordances for preschool children in the home and possibly other play-based settings. Their contribution to children's spatial learning and home practices will be examined in the near future as part of the study.

CONCLUSION

Game development has tended to follow an 'ages and stages' approach. Different to this conception of development, is our cultural-historical view of development where the focus is on how the child enters into, shapes and is shaped by the games, for realising spatial knowledge and reasoning. Our games will be used as part of a suite of resources to explore how parents and caregivers can help facilitate spatial learning. This new understanding is an important contribution towards efforts to lift STEM participation, especially for girls, through early intervention.

KEYWORDS

spatial reasoning, preschool children, games

Introduction

As technology becomes more ubiquitous to everyday life, the importance of Science, Technology, Engineering and Mathematics (STEM) knowledge and skills, today and into the future, becomes more critical, and the urgency to address this skill shortage ever more pressing (Australian Government, 2017). The early years play a vital role in future STEM learning (Campbell et al., 2018; McClure et al., 2017) and the Australian government acknowledged this with the release of a national STEM strategy that emphasised the need to invest in STEM education for children, including in the preschool years (Education Council, 2015). However, decreased rate of STEM enrolment, low female participation, and declined performance in mathematics are causes for concern (Australian Industry Group, 2015).

Understanding spatial play in home settings

Spatial reasoning skills are critical for STEM.

Spatial reasoning skills, the ability to visualise and manipulate objects and their environment in one's mind, has been shown to be critical for success in STEM fields (Wai et al., 2009). The reason is due to the spatial nature and high level of abstract thinking required in order to interpret the multitude of diagrams, charts, schematics and drawings that form a central part of their understanding (Verdine et al., 2014). Uttal and Cohen (2012) suggests that spatial reasoning skills may even be a "gatekeeper" for STEM success, and "those with low spatial abilities either do not go into STEM majors or dropout soon after they begin" (p. 168).

Spatial reasoning skills and mathematical skills are linked.

Spatial reasoning skills play a supportive role for mathematics, and its importance seems to increase with more advanced and abstract mathematics (Mix & Cheng, 2012; Smith, 1964). Mix and Cheng (2012), argued that

> *the relation between spatial skills and math is so well established that it no longer makes sense to ask whether they are related. Rather, we need to know why the two are connected…" (p. 206).*

Both improved spatial skills, and the associated improved mathematics skills, could hence combine to be one of the answers to lifting future STEM participation (Sorby et al., 2018).

There is a gender disparity in engineering.

Women are underrepresented in engineering (Kaspura, 2019) and other fields such as physics and mathematics (van Tuijl & van der Molen, 2016). There are a range of affective reasons preventing women from entering or remaining in engineering, including lack of parental support (Ge & Li, 2017), negative gender stereotypes (Thom et al., 2002), belief that engineering does not benefit society and humanity (Eccles, 2007), and unsupportive work cultures (Watt et al., 2017). While these are concerning issues that need to be addressed, one might wonder about other influencing factors.

There is a gender disparity in spatial performance.

In 2005, over 200,000 people in 53 countries took a six-item mental rotation test and a 20-item line angle judgement test as part of a survey conducted by the BBC. The men's average score was higher than the women's in every country (Lippa et al., 2010). In children, boys have been noticed to perform better than girls in spatial reasoning tests from as early as four years of age (Levine et al., 1999). Sorby et al. (2018) reported that while only 20% of first year engineering students were female, they made up 45% of the low scoring group on a spatial test who were then required to take a spatial intervention course.

Spatial reasoning skills can be learned.

Uttal et al. (2013) found spatial reasoning skills to be highly malleable based on a meta-analysis of 206 studies between 1984 and 2009. Spatial training was found to be effective and durable, and resulted in both near transfer (improvement in similar tasks) and far transfer (improvement in different, unrelated tasks). In a study of 58 girls and 58 boys in Grade 1, Tzuriel and Egozi (2010) found that boys outperformed girls on mental rotation tests, but the performance gap was eliminated following a training program.

We know very little about spatial experiences in early childhood.

Spatial skills are not innate, they are acquired through experiences (Davis et al., 2015). However, our knowledge about the early childhood experiences in the home that may influence the young children's spatial development is rather limited. There is a large body of research on the spatial skills of adults, adolescents, and school aged children, but relatively fewer studies involve very young children; those that do mainly focus on laboratory or institutional settings. Finding out more about how families may or may not contribute to spatial reasoning skills of their children can help with understanding what might be other early factors that contribute to the engineering gender disparity.

The influence of the home environment cannot be underestimated.

Parents play a key role in shaping children's values, interests and career aspirations (van Tuijl & van der Molen, 2016; Holmes et al., 2016). By as early as six or seven years of age, children already absorb gender and social class stereotypes (Bian et al., 2017; Chambers et al., 2018). These stereotypes strongly shape their beliefs about their capability, influencing their interests and how they invest their time and effort in childhood, with consequences for school subject choices and, subsequently, career options. If we only target secondary, or even primary aged children, we may be a few years too late. We need to predispose children to have the interest, capability and choice to pursue STEM pathways earlier.

Parents who believe in the importance of literacy and numeracy provide a high level of support to their children, incorporating literacy and numeracy learning into their everyday home practices (Evans & Shaw, 2008; DeFlorio & Beliakoff, 2015). We believe that by enlisting parental and early childhood educator support, and working with parents to explore opportunities for everyday spatial learning and making spatial learning another part of valued family practice, we can help children towards building a 'STEM is for me' identity.

Play is the primary source of development for preschoolers. We need to understand how play and play materials in the home contribute to children's spatial learning.

In the preschool years, play is the leading activity and the source of development (Vygotsky, 1967). Fleer (2018a) further emphasised the importance of play, arguing that, "without opportunities for imaginative play, children may find it difficult to imagine and use abstract concepts for learning later in school" (p.1). Children's play, however, does not just arise from within the child based on biological development, but rather in relation to environmental conditions such as parental values and available resources (Fleer, 2014).

Digital technology in the home offers possible learning affordances for children, in a complementary way to traditional toys.

Playing games help children learn (Lai et al., 2018). In certain cases, it may be easier for preschool children to manipulate a digital rather than a physical object, so digital technology provides learning opportunities through play for children which may not otherwise be available (Stephen, 2015). Digital technology also helps children develop "positive learning dispositions", such as "confidence, independence, and willingness to persist" (Stephen, 2015 p. 349). Well-designed games can provide opportunities for entering into imaginary situations and can promote abstract thinking and development of higher cognitive abilities (Verenikina et al., 2010; Lieberman et al., 2009). Therefore, providing engaging spatial games and apps may be a good strategy to help families give their children different kinds of opportunities for the development of spatial knowledge and reasoning.

The Conceptual PlayLab and the research being undertaken is Australia's first national 5-year programmatic study into the formation of STEM concepts in the preschool years. The overarching PhD research of the first author contributes to this programmatic study, and is focused on *how the home environment contributes to preschool children's development of spatial reasoning ability*. Part of the research involves creating games and apps that will be combined with existing resources, such as picture books, to be provided to families.

In this paper, we will discuss three mobile apps that have been created primarily to be used in the family home by children, with help and guidance by their parents or other caregivers. Instructions from and interactions with a capable and interested adult help sustain children's engagement with games and its associated play and learning (Stephen, 2015).

Approach

The study is guided by the cultural-historical theoretical framework.

Cultural-historical theory is based on a system of interrelated concepts, originally proposed by Lev Vygotsky, who argued against maturational/developmental theories, which view child development as a linear biological unfolding, and only measure children's completed development based on what they can do independently. In cultural-historical theory, the child's development is viewed as an iterative social or cultural process, where children develop through interactions with adults and more competent peers. By observing what children can do co-operatively with the guidance of an adult, we see their *maturing*, rather than *matured, fruit of development* (Vygotsky, 1998).

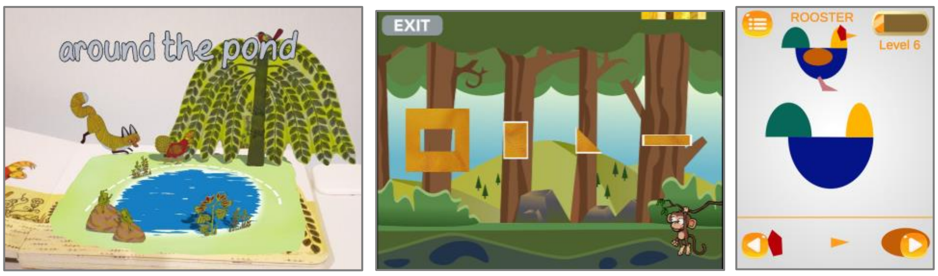
Furthermore, a dialectic relationship between the child and their environment exists, where the child is not just shaped by their social environment, but also contribute to shaping that environment, based on their affective relationship with that environment (Fleer, 2018b).

The digital resources are built using combined principles from spatial reasoning literature and the Conceptual Playworlds model of play-based learning.

In Conceptual Playworlds (Fleer, 2018a), adults play a central role in establishing a narrative, inviting children into a collective imaginary situation, posing a problem scenario, and sustaining their play as a play partner. Children learn concepts through emotional engagement with the story's characters and solving problems as part of their play.

Developed digital resources

We have developed three apps, each with playing instructions and explanatory notes for caregivers to raise awareness about the importance of early spatial experiences and provide suggestions for facilitating children's spatial learning through everyday activities. Screenshots of our three apps are shown in Figure 1 below. These apps are under continual development and improvement, and we welcome feedback and suggestions.



(a) (b) (c)

Figure 1. (a) Rosie (b) Winter Quilt (c) Fun Shapes

Augmented Reality for spatial relations and prepositional words

AR technology has emerged as a useful tool in educational contexts. In early childhood settings, parents of preschoolers were found to be in favour of the use of AR as a learning tool and felt that it improved their children's academic outcomes (Cascales et al., 2013).

Although there are a number of AR apps available where three-dimensional (3D) rendition of book images are shown, as far as we are aware, ours is the first app that utilises AR to demonstrate the specific concept of spatial relations or prepositional words.

Rosie

The book “Rosie’s Walk”, by Pat Hutchins (Hutchins, 2015) was chosen for this app. The book is about a hen called Rosie who goes for a walk around a farm, completely oblivious to a fox who is following her and trying to pounce on her at every opportunity. This book was chosen for its simple sentences, beautiful illustrations, potential for young children to be emotionally engaged with both the hen and the fox, and its affordance for many concepts to be discussed with children with respect to spatial learning and beyond.

When the user opens the app and hovers the mobile device over designated pages of the book with a sentence containing a prepositional word, such as ‘across’ or ‘over’, they will see a 3D animation of the page. Tapping ‘Play’ will Rosie to perform the action stated on the page, such as walking “over the haystack”, accompanied by a voice-over reading the text.

This app provides possibilities for children’s learning of prepositional concepts to be enhanced, and for families to consciously incorporate them into everyday activities.

The app runs on Android devices (v5.1.1 or higher), with both tablets and smartphones being supported. The device is required to have a camera and must support OpenGL 3. The app was built on the 3D-capable game engine Unity, using Vuforia as the AR framework because it is platform agnostic, providing an option to support iOS in future.

Mobile game apps for shape recognition and mental rotation

Winter Quilt

Winter Quilt is a game inspired by the “Thurstone test” mentioned in Levine et al. (1999), where children need to pick a shape that would join with another to make a complete square. In this game, the child is told the story of animals who live in a forest who have not had time to gather enough materials to keep warm because winter has arrived earlier this year. The child is asked to help them by making a quilt, by finding two shapes that would join to make a square. Each completed square is added to the quilt; the more completed squares, the bigger the quilt. Some pieces will need to be rotated in the child’s mind. Audio and visual feedback is provided for both correct and incorrect choices. An adult is encouraged to play the game with the child and help describe how the pieces rotate to fit together.

The Quilt Maker function allows the child to make their own quilt by using the completed squares and ‘stitching’ them together in any pattern they desire.

The app is coded using the Godot mobile application framework. It is designed to run and has been tested on a Nexus 9 tablet running Android v7.1 Nougat version or later. It scales to fit any tablet, as well as smartphones, but the user experience can be negatively affected on smaller phone screens due to the scale of the app and ability to easily select correct options. The app utilises single-point touch functionality, detecting finger presses and drags.

Fun Shapes

The game currently contains two puzzle worlds, Mouse Shapes world and Farm world. Mouse Shapes world is inspired by the book “Mouse Shapes” by Ellen Stoll Walsh (Walsh, 2017). Mouse Shapes is a picture book about three mice who try to run from a cat and scare him away. In the process, they create a number of figures by piecing together different geometric shapes. An adult is encouraged to read the book with the child, and the child can use the app to make up the figures shown on the pages of the book. The child can drag shapes from the toolbar and rotate them into position in the assembly area to match the target image. In Farm world, the child is presented with a series of figures of common farm objects, such as a tractor, a cow, a hen, or a barn, of varying difficulties, to construct.

The Movie Maker function allows the child to select the farm figures and create a short movie by recording their voice and the figures as they are moved and rotated on the screen.

The app is programmed using the game engine Unity (v2018.4.16f1), in C#. It is designed for use on a Nexus 9 tablet running Android API 21 Lollipop or later. The game play requires careful manipulation with two fingers, so while the app can be played on any Android device, a typical smartphone screen would be too small to play effectively.

By telling a story and presenting familiar things for the child to make, we hope to create a level of emotional engagement in the child and motivate them to solve the puzzles. The Quilt Maker and Movie Maker functions in the two apps are intended to provide further space for creativity, imaginative play, and exploration.

Home observation study – the next step

Data collection method

Digital video observations will be the main method to collect participant data, in addition to pre- and post-surveys, video interviews, and other artefacts such as photographs and drawings. This methodology is most suited to our research question because it allows for observations of children in their natural settings. Video observations are useful in documenting the family practice traditions and interactions, avoiding the pitfalls of studying the child as an entity separate from their social environment. Video observations also give the child a voice in research into their own development, aiding the iterative analysis of the different perspectives - the child's perspective and the parents' perspectives, as well as being useful in guiding interview questions with the participants using stimulated recall (Fleer, 2008). Due COVID-19, we are adapting our data collection methodology to include interviews and observations over videoconferencing, and participants' own video recordings.

Expected results

We are expecting to collect data on how parents use the provided resources to help children with their spatial language and thinking. The data may also provide insight into whether *parents* become more aware of spatial concepts and how the resources contribute (or not) to changes to family practices. We will also explore how support for children's spatial development differ based on parental STEM background and gender of the child.

Conclusion

STEM education is important across all stages of the pipeline and spatial reasoning ability has been found to be a strong enabler for STEM learning. There is a current gap in the literature on how the home environment contributes to young children's spatial development. In this paper, we have presented three newly created digital resources as cultural tools to amplify children's spatial development through imaginative play. The next steps will include a study to explore how parents can use these and other spatial resources, activities and tools to help facilitate spatial learning. This new understanding is an important contribution towards efforts to lift STEM participation rates for all, but especially girls, through early intervention. It will also contribute to addressing demands on increased cognitive outcomes for young children while preserving imaginative play in the preschool years.

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