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Augmented Reality interfaces for symbolic play in early childhood

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Abstract

Augmented Reality (AR) is an umbrella term for technologies that superimpose virtual contents onto the physical world. There is an emerging research focus on AR applications to improve quality of life for special user groups with diverse levels of age, skill, disabilities and knowledge.

Symbolic play is an early childhood activity that requires children to interpret elements of the real world in a non-literal way. Much research effort has been spent to enhance symbolic play due to its close link with critical development such as symbolic thought, creativity and social understanding.

In this thesis, I identified an analogy between the dual representational characteristics of AR and symbolic play. This led me to explore to what extent AR can promote cognitive and social development in symbolic play for young children with and without autism spectrum condition (ASC). To address this research goal, I developed a progressive AR design approach that requires progressive levels of mental effort to conceive symbolic thought during play. I investigated the usability of AR displays with the magic mirror metaphor to support physical object manipulation. Based on the progressive AR design approach and preparatory usability investigation, I designed an AR system to enhance solitary symbolic play, and another AR system to enhance social symbolic play. The effectiveness of each system was rigorously evaluated with reference to psychology literature.

Empirical results show that children with ASC 4-7 years old produced more solitary symbolic play with higher theme relevance using the first AR system as compared with an equivalent non-AR natural play setting. Typically developing children aged 4-6, using the second AR system, demonstrated improved social symbolic play in terms of comprehending emotional states of pretend roles, and constructing joint pretense on symbolic transformations using specially designed AR scaffoldings.

Declaration

This thesis is my own work and contains nothing which is the outcome of work done in collaboration with others, except where specified in the text. It is not substantially the same as any that I have submitted for a degree or diploma or other qualification at any other university and does not exceed the prescribed limit of 60,000 words.

Zhen Bai
September, 2014

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For Steve and our families.

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Glossary

Augmented Reality (AR) Technologies that superimpose virtual objects on reality with three primary characteristics: a combination of real and virtual, interactive in real time, and registered in 3-D (Azuma et al., 1997).

Autism Spectrum Condition (ASC) A neurodevelopmental condition that is associated with impaired social communication and interaction, and restricted and repetitive behaviours, interests or activities (American Psychiatric Association, 2013).

Divergent thinking A major cognitive process of creativity that involves exploring one's knowledge and generating a variety of ideas (Runco, 1991).

Eye-hand coordination The visuomotor skill that refers to using visual input to guide hand actions for object manipulation (Johansson et al., 2001).

Metacommunication in symbolic play A special communicative technique to establish, maintain and elaborate symbolic transformations of things, persons, actions and situations during joint pretense (Garvey, 1975).

Metaphor A HCI design tool to help users interact with unfamiliar user interfaces with concepts that are already understood (Blackwell, 2006).

Metarepresentation The second-order mental representation decoupled from the primary representation of reality, and is defined in the form of "Agent-Informational Relation-Expression." (Leslie, 1987).

Symbolic play An early childhood activity within which children play in a non-literal manner via object substitution, attribution of pretend properties, and imaginary objects (Leslie, 1987).

Symbolic thought The ability to think symbolically by using internal symbols and images (Piaget, 1962; Vygotsky, 1967).

Theory of mind The ability to understand mental states such as beliefs, desires, pretending and knowledge of oneself and others (Premack and Woodruff, 1978).

Usability "The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" (ISO, 1998).

Virtual Reality (VR) Technologies that generate computer-simulated environments by natural or mediated means, within which people have a sense of being in a real or imagined world (Steuer, 1992).

Chapter 1

Introduction

Augmented Reality (AR) technologies enhance people's perception of reality by overlaying virtual contents such as visuals and sound on physical environments (Azuma et al., 1997) (see Figure 1.1 as an example). In the past decades, AR has demonstrated its distinctive capacity to support tasks in fields such as maintenance, military, medicine, navigation, touring, entertainment and education for professional and general users (see Zhou et al., 2008a for a review).

In recent years, a research trend has gradually emerged for AR applications that assist special user groups, which have diverse levels of skill, disability, knowledge and age (Shneiderman, 2000). In particular, children are identified as special users of AR applications who, due to developmental factors, have significantly limited cognitive and motor abilities compared to adult users (Radu and MacIntyre, 2012). AR's integration of virtual and physical contexts provides special scaffolding for key aspects of children's learning processes, namely connection to real world context (Roschelle et al., 2000), manipulation of knowledge components (Glenberg et al., 2004), and exploration in three dimensions (Cohen, 2013).

Recognizing AR's potential, some researchers have investigated AR applications for children with diverse physical and cognitive disabilities (e.g. Hong et al., 2010; Richard et al., 2007), but evaluation techniques used for such applications remain qualitative and do not support rigorous quantitative analysis. Among activities in early childhood education, play is regarded as an essential activity for learning and development (Broadhead, 2004). In particular, this thesis focuses on a special form of play activity known as symbolic play.

Emerging in the second year of life, symbolic play involves an early represen-

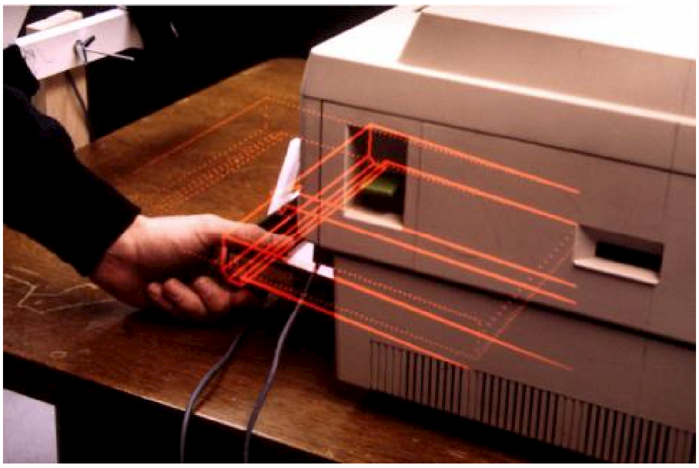


Figure 1.1: A laser printer maintenance AR application demonstrating how to remove the paper tray (Feiner et al., 1993).

tational ability to understand and use symbols when children substitute objects, enact roles and transform the here and now in which they are actually situated (Piaget, 1962). For example, a child may pretend that a banana is a telephone, a doll is unhappy, or there is a birthday party during symbolic play. Symbolic play is a term that is often interchangeable with pretend play, imaginative play and make-believe play. It is believed that symbolic play has critical links with important elements of cognitive and social development such as symbolic thought, language, creativity, social understanding and interaction (Duncan and Tarulli, 2003; Fein, 1981).

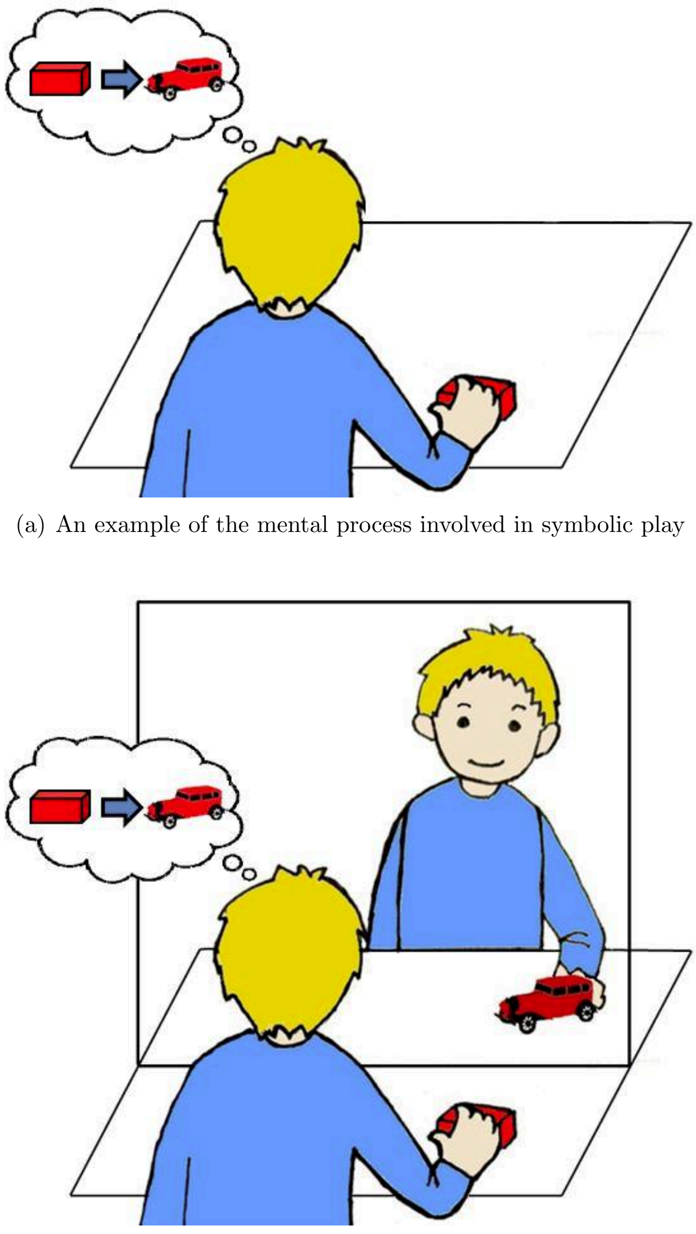
Numerous studies show that children with autism spectrum condition (ASC), a neurodevelopmental condition that affects about one percent of children in the UK (Baron-Cohen et al., 2009; Wing and Gould, 1979), are impaired with spontaneous symbolic play compared to typically developing and mentally challenged children (Baron-Cohen, 1987; Jarrold et al., 1996). Developmental differences in symbolic play are also found among typically developing children due to social, economic and cultural factors (Levy et al., 1992; Rosen, 1974; Smilansky, 1968). Therefore, much research effort has been spent to enhance symbolic play for both autistic and typically developing children in early childhood (see Barton and Wolery 2008 for a review).

1.1 Research Motivation

The core cognitive mechanism of symbolic play involves the dual mental representation of reality and pretense (Elkonin, 1969; Leslie, 1987). During symbolic play, mental representations of absent objects (e.g. a car) assimilated to present objects (e.g. a block) are evoked, which initiates the transformational processes from reality to pretense (Fein, 1975; Piaget, 1962; Sawyer, 1997). Therefore, the reference to reality is an indispensable element to establish pretense in symbolic play. Similarly, AR requires the reference to reality, such as objects and locations, on which to superimpose virtual representations. Consequently I identify a dual representational analogy between AR and symbolic play as illustrated in Figure 1.2. Based on this analogy, I propose the overall research goal of using AR technologies to enhance the cognitive and social development in symbolic play by taking advantage of this analogy to externalize mental representations of symbolic thought to the immediate reality.

AR is potentially beneficial for promoting symbolic play of both autistic and typically developing children. The lack of spontaneous symbolic play with autism is related to hybrid impairments in generating symbolic representations and associated play ideas (Jarrold, 2003; Leslie, 1987). First, by allowing children to observe and manipulate imaginary representations associated with the immediate reality, AR provides an alternative approach to explain and reinforce the otherwise opaque cognitive mechanism of symbolic play. Second, the visual illustrations of AR are expected to be beneficial to encourage children to generate open-ended symbolic representations and play ideas, which directly contribute to divergent thinking (Dansky, 1980b; Russ et al., 1999) but are not supported by concrete instructions given by adults in conventional interventions. Third, since the cognitive mechanism in symbolic play prompts children to comprehend pretense intentions of other players and mental states of pretend roles, enhancing this mechanism is an effective way to elicit the development of theory of mind, which pertains to understanding others' minds (Lillard, 2001b). Both divergent thinking and theory of mind are important abilities for academic and social readiness of children with and without ASC.

In spite of the analogy between AR and symbolic play, there has been little research effort into using AR to promote symbolic play. Most play-based AR applications take advantage of children's familiarity with physical objects (e.g. play



(a) An example of the mental process involved in symbolic play

(b) An example of AR-assisted symbolic play, with which the child sees an imaginary car visually overlaid on the block as if he is looking through a magic mirror

Figure 1.2: An illustration of the analogy between AR and symbolic play.

figures) to encourage ideation of imagined situations (e.g. Farr et al., 2010; Ryokai and Cassell, 1999). There is, however, a heavy dependence on the literal meanings of these physical objects while AR scaffoldings that particularly encourage symbolic transformations from physical to imaginary representations are absent (e.g. pretending a box is a train station). Meanwhile, research effort has been made to teach symbolic transformation mechanisms for children with ASC in a non-play Virtual Reality (VR) environment, in which representations of real life objects (e.g. a pair of trousers) and possible imaginary objects (e.g. a road) are shown side-by-side in a virtual environment (Herrera et al., 2008). VR, however, is limited in supporting symbolic play due to its isolation from immediate reality, since immediate reality seeds the conception of symbolic thoughts and associated play ideas.

I regard symbolic play as a fruitful research topic to extend our knowledge of designing and evaluating AR applications to support complex cognitive processes for special user groups from two perspectives. First, exploring the research goal helps to recognize AR's capacity to support complex cognitive processes and accommodate limited abilities of young children. By exploring the design space to encourage children to think in a more symbolic and divergent way during play, this thesis identifies new opportunities for AR applications to influence people's fundamental cognitive processes, while the majority of AR applications focus primarily on optimizing the user's access to certain knowledge without stretching the actual thinking pattern. Furthermore, since the target user group for symbolic play enhancement is children with limited cognitive and motor abilities due to age or atypical development factors, the findings in this thesis can reflect key usability considerations of designing AR applications for preschool and early primary school-age children with and without ASC, which remains a research gap in previous studies.

Second, investigating the research goal extends our knowledge of key considerations, informed by important aspects in developmental psychology literature of playful learning activities and children with ASC, to guide the design and evaluation of AR applications that support complex cognitive processes for special user groups. Symbolic play is an open-ended activity that requires a specific cognitive mechanism, namely symbolic thought. This characteristic differentiates symbolic play from other occupational or everyday tasks that are associated with definite goals and general access to knowledge. The identification of the thesis research goal relies on the understanding of the cognitive mechanisms of symbolic play. Such an identification process, therefore, establishes the fundamental importance of psychology literature to this thesis. This literature further contributes to the development of a progressive AR design approach (i.e. a design approach for AR which applies progressively higher levels of elicitation of mental effort) to enhance critical cognitive and social abilities involved in symbolic play. It also provides a reliable reference of rigorous evaluation methods for symbolic play enhancement, which is largely missing in previous studies as traditional time-error driven measurements no longer suit evaluation purposes for such open-ended activities involving complex cognitive processes. Moreover, addressing specific considerations of children with ASC who experience various difficulties in social interactions and communications can inform the design of rigorous evaluation methods of future AR applications for users with demanding needs.

1.2 Summary of Research Goal and Research Questions

1.2.1 Overall Research Goal

Explore to what extent AR can promote cognitive and social development in symbolic play for young children with and without ASC.

In this thesis I investigate the effectiveness of AR as visual scaffolding to promote symbolic play. Based on the representational analogy between AR and symbolic play, I develop a progressive AR design approach that requires increasing levels of mental effort to conceive symbolic thought during play. I then apply the proposed AR approach to the development of two consecutive AR systems to promote solitary and social symbolic play respectively for children with and without ASC. Based on findings of empirical evaluations of these two AR systems, I conclude that AR has positive effects in promoting cognitive and social development involved in symbolic play including symbolic thought, divergent thinking and theory of mind for autistic and typically developing children of preschool and early primary school age.

1.2.2 Research Questions

Research Question 1: *What are key design considerations of AR systems that promote symbolic play for young children with and without ASC*?

Research Question 2: *How usable is the magic mirror display metaphor in supporting symbolic play for young children*?

Research Question 3: *What are key considerations to rigorously evaluate the effectiveness of AR systems in promoting symbolic play for young children with and without ASC*?

The above research questions are established through the literature review in Chapter 2. In particular, the first research question is formed in Section 2.2 and investigated in Chapters 3, 5 and 6. The second research question is formed in Section 2.3 and investigated in Chapters 4, 5 and 6. The third research question is formed in Section 2.3 and investigated in Chapters 5 and 6.

1.3 Summary of Research Contributions

Contribution 1: *Confirm the positive effects of AR to promote symbolic play for young children with and without ASC.*

Contribution 2: *Provide a progressive AR design approach to promote symbolic play for young children.*

Contribution 3: *Confirm the usability of the magic mirror display metaphor to support physical object manipulation, and associated human-computer and social interactions.*

Contribution 4: *Outline key considerations for rigorous evaluation of AR systems in supporting tasks that involve complex cognitive processes and young children with ASC.*

1.4 Thesis Structure

In Chapter 2, I first conduct an in-depth literature review of AR and symbolic play as the technological and theoretical research background of this thesis. Through this review, I identify the dual representation analogy between AR and symbolic play. This raises the initial motivation towards the research goal of using AR to promote symbolic play for children with and without ASC. With the research goal determined, I then review detailed AR research on child users to obtain state-of-the-art knowledge and challenges for designing and evaluating AR applications to support complex cognitive tasks for children. Three main research gaps are identified including AR applications for symbolic play enhancement, usability of the AR magic mirror display metaphor to support physical object manipulation, and rigorous evaluation methods for complex tasks for demanding child users. These research gaps lead to the research questions of this thesis respectively.

In Chapter 3, I investigate the detailed cognitive mechanism of symbolic play and identify symbolic thought as the essential element of symbolic play that triggers the mental processes of divergent thinking and theory of mind. Based on this investigation, I further elaborate the representational analogy between AR and symbolic play as proposed in Chapter 2. In view of this analogy, I propose a progressive AR design approach to enhance symbolic thought, divergent thinking and theory of mind in symbolic play. This approach is applied and evaluated in Chapter 5 and 6.

I present three empirical studies in Chapters 4, 5 and 6, with each study investigating a specific set of questions relating to the usability of AR magic mirror and its capacity in supporting symbolic play for young children with and without ASC. In Chapter 4, I present a preparatory usability study carried out in parallel with the investigation of the AR design approach to enhance symbolic play in Chapter 3. This study explores adult user performance in bimanual manipulation of physical objects with the AR magic mirror display metaphor. In response to the conceptual bias on poorer eye-hand coordination due to mirror reversal, I conduct a novel experiment to compare participants' object manipulation performance when following rotational cues between see-through window and magic mirror display metaphors. Findings show that participants' overall performance under the mirror view was comparable to the see-through view. This informs the design of AR systems using the magic mirror metaphor to enhance symbolic play in

Chapters 5 and 6. Further usability issues of young children interacting with an AR magic mirror are explored in these two chapters as well.

In Chapter 5, I design an AR system with the magic mirror metaphor to explore the potential of AR to promote solitary symbolic play for young children with ASC. This design is developed based on an integration of the progressive AR design approach proposed in Chapter 3, and literature of restricted play interests of children with ASC. Findings of an empirical experiment involving autistic children aged four to seven confirm that the AR system can help participants to carry out symbolic play more frequently with longer duration, and regulate play ideas more consistent to suggested themes compared with a non computer-assisted setting. This study confirms the fundamentals of the progressive AR design approach to enhance symbolic mental processes for children with ASC. I summarize a rigorous evaluation approach of applying symbolic play and autism literature to guide the design of evaluation methods of AR systems for symbolic play enhancement. In addition, the study confirms that autistic children with fine motor difficulties as young as four years old can manipulate physical play materials to carry out symbolic play ideas under the magic mirror view, while associated usability considerations are discussed. The above outcomes inform the design and evaluation of AR systems for social symbolic play enhancement in Chapter 6.

In Chapter 6, I continue investigating the potential of AR to promote social symbolic play for typically developing children when symbolic thoughts are tightly integrated with social understandings. I develop the second AR system, FingAR Puppet, to promote social symbolic play by further applying the progressive AR design approach proposed in Chapter 3. Findings of an empirical study with typically developing children aged four to six show that the FingAR Puppet system can effectively encourage children to express and understand emotional states of pretend roles, and make more explicit verbal communication about symbolic transformations on open-ended AR materials. Observations of the study confirm that the shared AR magic mirror can efficiently support object manipulation and associated human-computer and social interactions involved in social symbolic play. The primary usability considerations of the AR magic mirror to support social play activities are discussed in detail. These findings are useful to inform the design of future AR systems that promote social symbolic play for children with ASC.

In Chapter 7, I first outline major findings in response to the research goal and research questions of the thesis. I then elaborate the contributions and related implications resulting from these findings. Lastly, I discuss directions for future research and draw the conclusions of this thesis.

1.5 Conclusion

This chapter laid the foundation of this thesis. I introduced the technological and theoretical research contexts of this thesis, which established the main research goal and its importance to the above research contexts. I then proposed three research questions in seeking for answers to the research goal and summarized the main contributions of this thesis. Lastly, I presented an overview of research covered in each chapter. The remainder of this thesis presents a detailed description of the research.

1.6 Publications

1. Bai, Z., Blackwell, A. F., and Coulouris, G. (2013, October). Through the looking glass: Pretend play for children with autism. In 2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), (pp. 49-58). IEEE.

2. Bai, Z., and Blackwell, A. F. (2013, October). See-through window vs. magic mirror: A comparison in supporting visual-motor tasks. In 2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), (pp. 239-240). IEEE.

3. Bai, Z., Blackwell, A. F., and Coulouris, G. (2013, April). Can we augment reality with mental images to elicit pretend play?: a usability study. In CHI'13 Extended Abstracts on Human Factors in Computing Systems (pp. 1-6). ACM.

4. Bai, Z., Blackwell, A. F., and Coulouris, G. (2012, November). Making Pretense Visible and Graspable: An augmented reality approach to promote pretend play. In 2012 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), (pp. 267-268). IEEE.

5. Bai, Z. (2012, June). Augmenting imagination for children with autism. In Proceedings of the 11th International Conference on Interaction Design and Children (pp. 327-330). ACM.

6. Bai, Z., and Blackwell, A. F. (2012). Analytic review of usability evaluation in ISMAR. Interacting with Computers, 24(6), 450-460.

Chapter 2

Literature Review

In Chapter 1, I provided a brief introduction of the research background of this thesis and described the overall research goal and research questions. In this chapter, I conduct the literature review of key research contexts that contribute to establishing the proposed research goal and research questions, which help to define the scope and focus of this thesis. These research contexts include AR, symbolic play and AR for children.

In Section 2.1, I review AR as the technological background of this thesis from four aspects: dual representation, technology, application, and evaluation. State-of-the-art development, challenges and opportunities in each aspect are discussed, which frames a set of initial research interests that lead to the formation of the overall research goal in Section 2.2.

In Section 2.2, I review symbolic play as the theoretical background of this thesis. The analogy between AR and symbolic play, and the motivation of exploring the capacity of AR in supporting cognitive tasks for special user groups jointly lead to the research goal: "*Explore to what extent AR can promote cognitive and social development in symbolic play for young children with and without ASC*".

In Section 2.3, I review literature of AR research for children to present detailed justifications for the three research questions of this thesis. The review covers AR applications for children, technological considerations for symbolic play, and usability evaluation challenges. Three main research gaps are identified including AR applications for symbolic play enhancement, AR displays with the magic mirror metaphor to support physical object manipulation, and rigorous evaluation for AR systems involving complex cognitive activities and young children with relatively low cognitive and motor skills.

2.1 Augmented Reality

AR is defined as technologies that superimpose virtual information on physical surroundings and allow user interaction in real time (Azuma et al., 1997). It provides a distinct user experience from conventional graphical user interfaces by extending users' knowledge space without switching between real and virtual contexts. AR has been applied in various domains such as manufacturing, medicine, maintenance, education, entertainment and more (see Zhou et al., 2008a for a review). In this section, I provide an overview of AR to illustrate the technological background of this thesis. First I introduce the dual representation of physical and virtual objects as the core characteristic of AR (Section 2.1.1). Second, I present key technologies that realize the dual representation characteristic of AR (Section 2.1.2). Third, I investigate the trend and opportunities of AR applications (Section 2.1.3). Last, I present a survey of AR evaluation methods and recognize related challenges (Section 2.1.4). The state-of-the-art of AR and its future opportunities addressed in the following sections form the essential research motivation of the thesis from the AR perspective.

2.1.1 Dual Representation of AR

The dual representation of physical and virtual objects is the essential representational feature of AR. In this section I investigate the representational variation among AR interfaces, which indicates potential directions for future studies. First I review existing frameworks addressing the degree of AR dual representation. Second, I group AR applications into three categories in terms of their dominant representation, and identify the exploitation of integrated representation as the primary research focus that enriches our understanding of the core value of AR.

According to the virtuality continuum proposed by Milgram and Kishino, AR resides between the real environment consisting of exclusively real objects and the virtual environment consisting of exclusively virtual objects (Milgram and Kishino, 1994)(Figure 2.1). Parallel to the virtual continuum, Grasset et al. (2008) proposed the physicality continuum according to the amount of physical

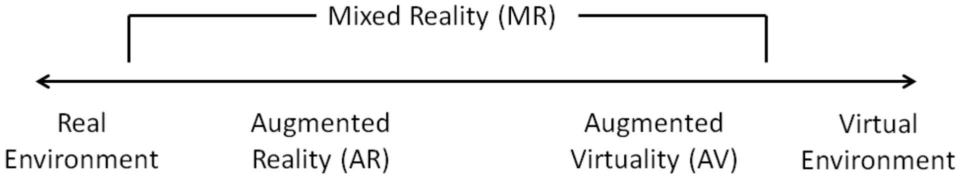


Figure 2.1: A redraw of the virtuality continuum proposed by Milgram and Kishino (1994).

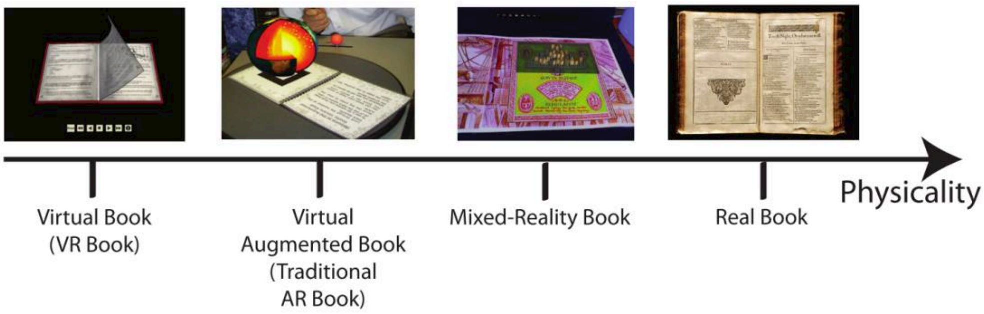


Figure 2.2: The physicality continuum proposed by Grasset et al. (2008).

elements presented in an AR interface (Figure 2.2), and promoted to combine virtual and physical contents of an AR book in a more seamless and meaningful way. The two frameworks indicate that AR occupies a range within the physical-virtual continuum of Mixed Reality, and that within the range of AR there are various levels of integration between physical and virtual contents.

To further investigate the physical-virtual continuum of the representational space of AR interfaces, I group them into three categories according to the dominant representation: physical, virtual and integrated representation (Figure 2.3). I define the dominant representation of AR as the components to which the users mainly attend during interactions with an AR interface.

Physical Representation as Dominant Representation

In this category, physical objects are the leading representation to which users attend, while virtual objects are sparsely registered on these physical objects to improve users' task performance. Users interact with physical objects under the superimposed virtual instructions in similar ways as they do in real life. It is commonly seen in task-assisted AR applications, such as maintenance, assembly and

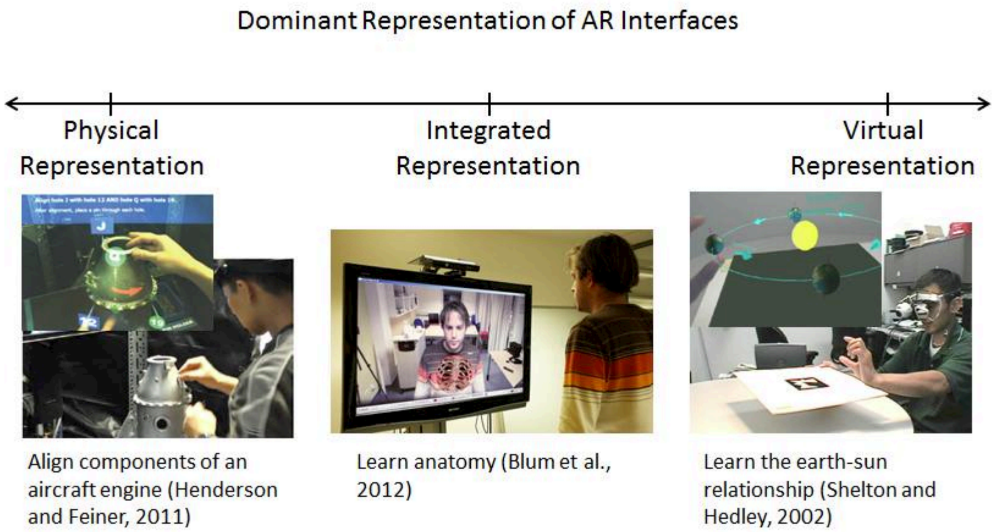


Figure 2.3: The dominant representations of AR interfaces.

navigation. For example, during the task of aligning components of an aircraft engine (Figure 2.3 left) (Henderson and Feiner, 2011), a user mainly concentrates on operating the physical engine and only refers to the facilitative virtual contents for instructions when needed.

Virtual Representation as Dominant Representation

In this category, virtual objects are the leading representation to which users attend. Some representative application domains under this category are education, gaming and industrial design. For example, the right image in Figure 2.3 shows a user learning the earth-sun relationship when observing a 3D animation superimposed on a marker-attached board (Shelton and Hedley, 2002). In this case, the physical object is merely an interaction device to support the user to observe the virtual objects from different perspectives, without real representational meaning associated between the physical objects and the educational contents.

Integrated Representation as Dominant Representation

In this category, users attend to the integrated representation combined with both physical and virtual objects simultaneously. The AR book developed by Grasset et al. (2008) as mentioned earlier is a representative example of an AR application with integrated representation. Another example, as illustrated in Figure 2.3 (middle) is an anatomy education AR application by which a user studies CT-scan anatomy knowledge projected on his/her own body (Blum et al., 2012). Both examples involve users paying equal attention to the physical and virtual objects, which constitute the integrated representation of the target task.

When physical or virtual objects are the dominant representations of an AR interface, the way that physical and virtual objects link to each other are loosely defined as long as it is sufficient to facilitate interaction towards the dominant representation. Only in the AR interfaces when physical and virtual objects are combined in a more sophisticated way to construct the integrated representation as a whole, the advantages of the rich expressiveness of both virtual and physical objects are fully exploited. Therefore, I am motivated in this thesis to explore the capacity of AR with seamless integrated representations to support tasks involving complex cognitive processes. In the next section, I present core AR technologies that support the dual representation characteristic of AR.

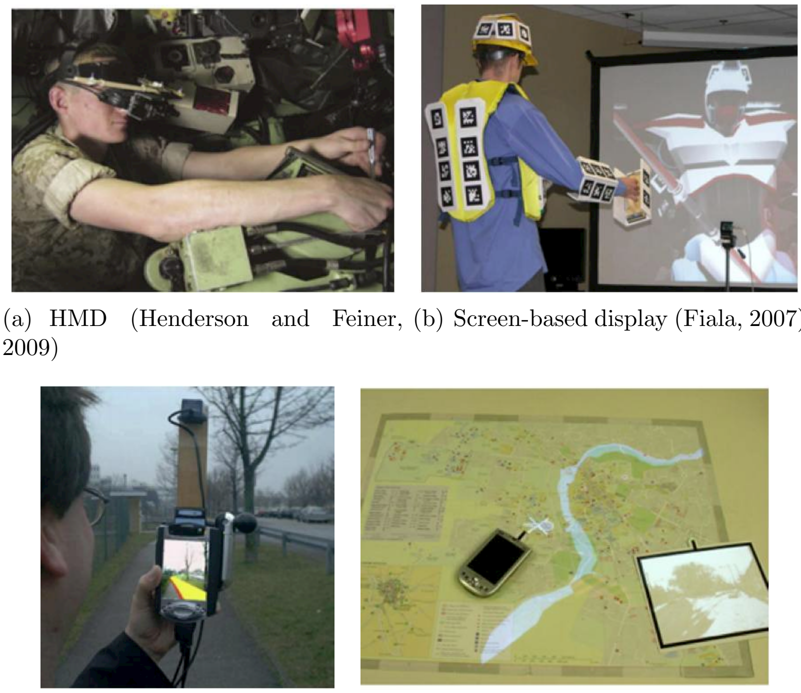
2.1.2 AR Technologies

Display and tracking are the two fundamental AR components that determine the user's interaction experience with an AR system. In this section, I introduce the state-of-the-art development of these two components, including the primary technologies and the corresponding advantages and disadvantages.

AR Display

In the past decades, efforts to advance displays for computing devices have constantly extended AR technology. In the following paragraphs, I focus on reviewing four types of AR display that are most commonly applied in AR applications: head-mounted display (HMD), screen-based display, handheld display and projection-based displays. Technological, human, and economic factors of each display are discussed, which are important considerations when designing for AR applications.

HMD refers to devices worn on one's head with a display in front of one's eyes (Figure 2.4(a)). Based on the vision source, HMDs are classified as either optical or video see-through hardware, with different strengths and limitations (Azuma et al., 1997; Rolland et al., 1995). The optical HMDs overlay virtual



(a) HMD (Henderson and Feiner, 2009) (b) Screen-based display (Fiala, 2007)

(c) Handheld display (Narzt et al., 2003) (d) Projection-based display (Reitmayr et al., 2005)

Figure 2.4: Examples of AR displays.

contents directly on an optical view of the world. Although providing a close to naked eye view of the world, the optical HMDs encounter limitations such as lack of occlusion effects since virtual contents are not opaque, and a limited field of view. Meanwhile, the video HMDs register virtual contents in a video stream of the environment captured by mounted camera. The video feed mitigates major limitations of the optical HMDs, however, it encounters other limitations such as: delay between the video and the real world view, loss of resolution of the real world, and not being able to access the real world view when powered off. Other known factors that impede the adoption of HMD in AR systems for daily activities include cost, safety and comfort.

Screen-based displays such as desktop monitors and large projection screens (Figure 2.4(b)) are the most common displays used in personal AR systems. Compared to HMDs, screen-based displays are more accessible for general users, but with a lower level of immersion due to the limited screen size (Milgram and

Kishino, 1994). Since screen-based displays are also video-based, they share similar advantages and limitations to video see-through HMDs as discussed above. Screen-based displays support users' bimanual manipulations with physical and virtual objects, while the active area is often limited to the room size.

Handheld displays such as Tablet PCs, Personal Digital Assistants (PDA) and smartphones (Figure 2.4(c)) are special types of screen-based displays with small-sized screens that fit a user's hand. Since the creation of the first standalone AR system on an unmodified PDA a decade ago (Wagner and Schmalstieg, 2003), mobile handheld displays have become popular thanks to the recent advances of computing and sensor capacities (e.g. camera, GPS (global positioning system), inertial, gyroscope). Handheld displays support high mobility, but require the user to spare at least one hand to hold it during interactions, which unavoidably affects bimanual manipulation of both virtual and physical objects.

Projection-based displays project virtual contents onto physical objects ranging from flat surfaces to complex scale models. The difference between projection-based displays and screen-based displays using a projector is that with the former display, the virtual contents are registered on the projection surface, while with the latter one, the projection surface simply functions as a flat surface to receive projection but no registration is involved. Projection-based display has no loss of resolution of the real world. In addition, users do not need to wear or carry additional equipment to perceive the augmentation. The large field of view is particularly suitable for collaborative interaction. Limitations of projection-based display includes: (1) not suitable for outdoor usage due to the requirement of light contrast to ensure the perception of projected contents; (2) the 3D quality of virtual objects is constrained due to the high dependence on topographical properties of the projection surface; (3) single projector systems often cause virtual contents to be occluded by shadows, which can be mitigated by the use of multiple projectors with a considerable cost increase.

AR Tracking

Besides displaying technologies, an AR system has to recognise and track objects of interest in the real world to which virtual contents are anchored. These objects of interest can be of many different physical forms, such as artificial objects (e.g. 2D markers (Kato and Billinghurst, 1999)), real objects (e.g. a printer (Feiner et al., 1993)), locations (e.g. GPS coordinates (Feiner et al., 1997)) and environment (e.g. an office table top (Henry et al., 2012)). There are two main groups of tracking technologies according to previous surveys, namely vision-based and sensor-based tracking (Carmigniani et al., 2011; Papagiannakis et al., 2008).

Vision-based tracking applies computer vision technologies to track objects of interest using cameras. Marker-based and markerless tracking are the two major vision-based tracking technologies. Marker-based tracking detects artificial markers intentionally placed in the environment, such as passive paper-based 2D markers (Kato and Billinghurst, 1999) (Figure 2.4(b)) and active LEDs (Naimark and Foxlin, 2005). Marker-based tracking is robust and computationally efficient, and therefore it has been widely used with indoor AR systems. Recently, a number of approaches have been developed to track objects and environments in a markerless manner (see Klein, 2006 for a review). The pose of target objects is estimated based on known 2D templates (Jurie et al., 2002), 3D models (Drummond and Cipolla, 2002; Lepetit and Fua, 2005) or a hybrid of template and model (Pressigout and Marchand, 2006). Although there are constant efforts to decrease computational complexity and simplify procedures such as calibration, modeling and tracking recovery, future work is still needed to make markerless tracking more feasible to cope with situations in the real environment.

Sensor-based tracking uses sensors such as GPS, RFID (radio frequency identification), accelerometers, gyroscopes, and magnetic sensors to track objects of interest. The accuracy and range of tracking vary diversely among different sensors. For example, GPS is commonly used in location-aware mobile AR applications such as tourism (Feiner et al., 1997) and navigation (Narzt et al., 2003). Radio-based sensors such as RFID and active badges are often deployed for indoor object tracking in domains such as manufacturing (Stiefmeier et al., 2008) and smart offices (Want and Hopper, 1992). Magnetic sensors, accelerometers and gyroscopes are used in hybrid methods for accurate object tracking within a small area (Kiyokawa et al., 1999; Livingston et al., 2002).

Sensor-based tracking is fast and robust, but in some cases drifts over time due to noise accumulation (e.g. magnetic sensors, accelerometers). On the other hand vision-based tracking produces low jitter and drift, but performs slower due to higher computational requirements with intermittent tracking failure under fast motion or occlusion. Therefore, much research has probed hybrid tracking methods integrating both vision-based and sensor-based approaches to provide more efficient and reliable tracking (Foxlin et al., 2003; Klein and Drummond, 2003; Reitmayr and Drummond, 2006).

2.1.3 Trends in AR Applications

As AR technologies mature, there is an emerging effort to explore new AR applications. In this section, I identify two trends of AR applications over the past decades: the emergence of personal AR applications, and the extension of subject to special user groups (e.g. people with special needs, elderly and children). The latter trend motivates me in this thesis to uncover AR opportunities to facilitate a special group of users, namely children with and without special needs whose cognitive and motor skills are limited due to developmental factors.

The first trend of AR applications is a gradual shift from professional users to general users. Since the term of AR was first coined in the 1990s (Caudell and Mizell, 1992), there has been a long history of applying AR technologies in highly professional domains such as military, medical and industrial settings (Azuma et al. 1997; Fite-Georgel 2011 for reviews). AR applications in these domains require efficient displays and high tracking accuracy. Meanwhile, these organizations can often afford the expensive cost of equipment, deployment and maintenance and the target users are specialists who are well trained to adapt to the AR environment.

In recent years, AR applications to support personal tasks in our day-to-day life have been more extensively explored. With the release of the well-established ARToolKit open source library (Kato and Billinghurst, 1999) and ever-increasing hardware capabilities (e.g. powerful computation devices, high resolution displays and cameras, and more accurate sensors), rapid development of AR applications became feasible for the general research and industry communities. Some recent AR user scenarios include navigation (Narzt et al., 2006), touring (Lee et al., 2012), personal information assistance (Antoniac and Pulli, 2001), education (Blum et al., 2012; Kaufmann, 2002), and gaming (see Tan and Soh 2010 for a review).

The second trend of AR applications in recent years is extending the end-user group from general adult users to special users with a diverse level of skills, knowledge, age, gender, disabilities, culture and so forth (Shneiderman, 2000). There has been a long tradition of accessibility research in the field of Human-Computer

Interaction (HCI), which pertains to enabling users with various physical and mental abilities to equally access and benefit from information technologies (Gregor et al., 2002). Knowledge obtained during such inclusive research is not only informative for design practices supporting the target user group, but also beneficial to a broader range of users (Bergman and Johnson, 1995).

There are several recent AR applications that facilitate rehabilitation and learning tasks for users with physical or mental disabilities (e.g. adult patients with post-stroke symptoms (Luo et al., 2005; Regenbrecht et al., 2011), Parkinson's disease (Riess, 1999), vision or hearing impairments (Amemiya et al., 2004; Helal et al., 2001) and older people (Kim and Dey, 2009)). In particular, child users are distinct from general adult users due to their diverse motor and cognitive abilities in different developmental stages (Radu and MacIntyre, 2012). There are several AR systems designed to enhance cognitive and social development for children with and without disabilities, which contribute to the immediate research background of this thesis and will be extensively reviewed in Section 2.3.

2.1.4 Usability Evaluation for AR Systems

There has been a rapid increase of research efforts in usability evaluation as user scenarios supported by AR systems become more and more complex in recent years. According to the ISO definition, usability consists of three distinct aspects: (1) effectiveness: the accuracy and completeness with which users achieve certain goals; (2) efficiency: the efficiency of achieving certain goals with provided resources; (3) satisfaction: the user's comfort with and positive attitudes towards the use of the system (ISO, 1998).

In the following paragraphs, I present a summary of usability evaluation techniques and challenges based on the review of papers published in the International Symposium of Mixed and Augmented Reality (ISMAR) in the ten years from 2001 (Bai and Blackwell, 2012). As the leading international conference exclusively focused on AR, ISMAR attracts the leading research and provides an annual snapshot of state-of-the-art AR technologies and applications. Therefore I use ISMAR as a representative sample of the research concerns considered most relevant by leaders in the AR field.

Evaluation Techniques

There are four main evaluation techniques involved in the paper sample: quantitative empirical, quantitative and qualitative empirical, analytical, and informal. These evaluation techniques are referenced by a recent review of evaluation techniques in the HCI literature (Barkhuus and Rode, 2007), which divided these along two dimensions: empirical vs. analytical and quantitative vs. qualitative. Empirical methods typically require a group of potential users to participate in an evaluation, while analytical methods require only a smaller group of expert analysts. Quantitative evaluations analyse numeric data with statistical approaches to characterize a sample that reflects the usability needs of the entire potential user group (e.g. experimental performance measures and questionnaires). Qualitative evaluation gathers narrative data about users' subjective experiences or their behaviour while using the system (e.g. interviews, observation, open-ended questions). In addition, informal evaluations are those conducted in a non-controlled experiment without a pre-defined structure (e.g. randomly selected users were asked how they like the system). These evaluation techniques provide the foundation of designing experiments to examine the effectiveness of AR applications to support specific activities. I identified an increasing number of studies applying formal empirical evaluation methods (Figure 2.5). In particular, the proportion of research involving both qualitative and quantitative evaluations grew significantly between 2007 and 2010.

Evaluation Challenges

In spite of the recent trend of including both quantitative and qualitative methods into usability evaluation, there are several challenges remaining with emerging AR applications aiming to accommodate everyday scenarios for users with various demands. While the metrics of satisfaction remain similar, the effectiveness and efficiency differ significantly between expert, general and special users. For AR systems to support high occupational tasks such as those in military and corporations, short completion time and high accuracy are usually the two foremost effectiveness and efficiency measurements. For AR systems to support activities involving more complex or open-ended cognitive processes (e.g. education, art and entertainment), a large portion of research only focuses on UX (User Experience) factors such as general expert and user feedback, with the specific system

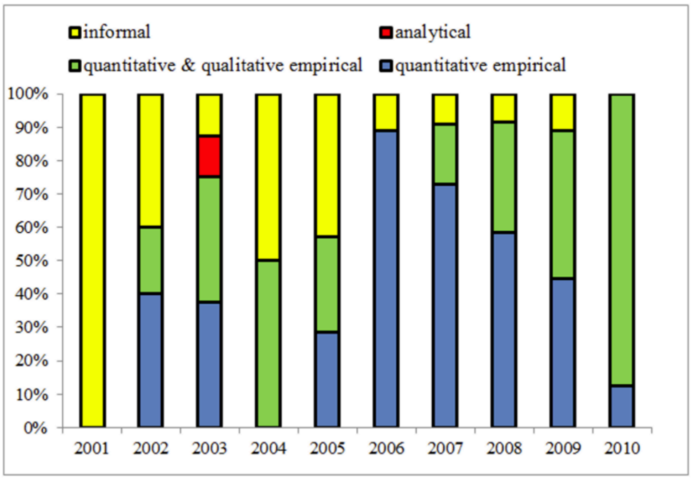


Figure 2.5: Proportion of ISMAR publications according to their usability evaluation approaches.

effectiveness in achieving target goals unexamined. Additionally, unlike occupational tasks where the users are trained to adapt to functionalities of the AR application, learnability becomes an important efficiency factor for novice users and special users with impaired or limited abilities. Therefore, the lack of rigorous evaluation methods increases demand for valid and reliable measures that accommodate the increasing complexity of AR applications.

Bearing in mind the latest development of AR technologies as well as challenges and opportunities of AR applications, in the next section I review a particular human activity, namely symbolic play in early childhood, which leads to the overall research goal proposed in Section 1.1.

2.2 Symbolic Play in Early Childhood

Recognizing children as a special user group that can especially benefit from AR technologies in the previous section, I explore the theoretical foundation of using AR to promote a special category of childhood activity named symbolic play. In Section 2.2.1, I present an overview of symbolic play and propose an analogy between symbolic play and AR. This is followed with investigation of impaired solitary symbolic play among children with ASC (Section 2.2.2), and individual differences of social symbolic play among autistic and typically developing children (Section 2.2.3). Intervention methods and limitations are explicated respectively. Based on the above review, the research goal of the thesis is raised and the potential benefits are justified.

2.2.1 Overview of Symbolic Play

Symbolic Play Development

Symbolic play is a leading activity of early childhood, through which critical cognitive and social development occurs (Duncan and Tarulli, 2003; Elkonin, 2005). It is often described as pretend play, imaginative play and make-believe play (Fein, 1981). During symbolic play, children substitute objects, enact roles and transform the here and now in which they are actually situated (Garvey and Berndt, 1975; Leslie, 1987). Symbolic play requires an early representational ability to understand and use symbols (Piaget, 1962) and it contributes to the development of abstract thought with integral aspects of social practice (Vygotsky, 1980).

Symbolic play appears during the second year of life in a solitary form (McCune-Nicolich, 1981). It gradually shifts to social symbolic play around the latter half of the third year when children start to play in groups as their symbolic, language and social abilities mature (Bretherton, 1984; Iwanaga, 1973; Rubin et al., 1978; Sanders and Harper, 1976). Social symbolic play advances between three to six years and is mainly developed in the form of sociodramatic play or fantasy play (Fein, 1981). The former involves events and themes within children's real life experience while the latter involves themes that are distant from individual experience (Saltz et al., 1977; Smilansky, 1968).The representational aspect of social symbolic play differentiates it radically from other forms of play such as sensorimotor play, functional play and constructive play.

Importance of Symbolic Play

Symbolic play is believed to have a strong association with cognitive and social development. For cognitive development, symbolic play has demonstrated positive contributions in language (Andresen, 2005; Levy et al., 1992), creativity (Dansky, 1980a,b; Johnson, 1976; Pearson et al., 2008; Sutton-Smith, 1975), reasoning (Richards and Sanderson, 1999), problem solving (Rosen, 1974; Shores et al., 1976) and self-regulation (Whitebread and O'Sullivan, 2012). Symbolic play involves the ability to form mental images of imaginary objects and associate stored images with present perception (Piaget, 1962; Ungerer et al., 1981), which is reckoned as the essence of the formation of symbols (Hammes and Langdell, 1981). During symbolic play, children have to control play actions in response to imaginary ideas instead of present situations (Pederson et al., 1981). Therefore, symbolic play is beneficial for children to practice free flow of association, symbol substitution, idea recombination, representation manipulation and affective relations, all of which are important for the development of flexibility and divergent thinking (Fein, 1987; Russ, 1998). Furthermore, research shows that symbolic play has an especially beneficial effect on counterfactual reasoning, which is closely linked with causal reasoning and understanding of possibilities in adulthood (Beck et al., 2006). This is because playful pretense contexts facilitate young children to reason about thoughts that are contradicted to their empirical knowledge (Buchsbaum et al., 2012; Dias, 1990; Weisberg and Gopnik, 2013).

In addition to cognitive development, symbolic play is found to correlate with critical social skills such as social interaction (Connolly et al., 1988; Rubin et al., 1978; Singer, 1976; Smilansky, 1968), social support (Charlesworth and Hartup, 1967; Levy et al., 1992), intersubjectivity (Göncü, 1993) and multiple perspectives (Burns and Brainerd, 1979; Schwebel et al., 1999). In particular, extensive research indicates a close relationship between social symbolic play and theory of mind, the ability to understand mental states such as beliefs, desires, pretending and knowledge of oneself and others (Astington and Jenkins, 1995; Dunn and Cutting, 1999; Hughes and Dunn, 1997; Leslie, 1987; Lillard, 2001b; Premack and Woodruff, 1978; Schwebel et al., 1999; Seja and Russ, 1999; Wellman, 2002; Youngblade and Dunn, 1995). It is suggested that social symbolic play leads to theory of mind development when children: (1) simulate and respond to mental states of pretend roles, such as beliefs, desires and emotional responses; (2) propose joint pretense about roles, props and events among players (Lillard, 2001a; Schwebel et al., 1999). Although the causal relationship remains inconclusive between social symbolic play and these development aspects, recent researchers believe that there is a reciprocal relationship between play and brain development (Fromberg and Bergen, 2006). This indicates that certain developmental skills are enhanced by social symbolic play while play behaviours become more complex as these skills advance over time.

Analogy between Symbolic Play and AR

Unlike operational or everyday tasks in which people perceive and interact with the physical world in a literal way, symbolic play requires people to conceive non-literal interpretations of the physical world. Thus understanding the cognitive mechanism of such non-literal conception becomes critical to identify the specific potential of AR to enhance symbolic play.

First, symbolic play involves a series of transformational mental processes, within which "characteristics of the immediate environment become subordinated to what is essentially a mentally initiated activity" (Fein, 1975). Transformation of objects is the earliest form of symbolic play when realizing improvisational themes under limited material resource (Sawyer, 1997).

Second, symbolic play relies on the dual representation of reality and pretense. Common forms of symbolic play include role shifting (e.g. pretend to be the mom), object substitution (e.g. use a banana as a telephone), pretend property (e.g. pretend the table is wet), and imaginary object (e.g. pretend to clean the floor with an imaginary broom) (Elkonin, 1969; Fein, 1975; Leslie, 1987). Mental representations of the immediate environment (e.g. self, banana, table, hand) and the nonfactual representations (e.g. mom, telephone, wet, broom) are the two indispensable ends of transformation in order to establish symbolic thought.

As described in Section 2.1.1, AR relies on dual representation of physical and real objects and requires references to the immediate reality such as objects and locations to superimpose virtual representations. Based on the dual representation nature of both symbolic play and AR, as well as their dependence on the immediate reality, I identify a representational analogy between symbolic play and AR which is elaborated in Chapter 3. This analogy potentially enables AR to reinforce the cognitive mechanism of symbolic play by externalizing mental representations of symbolic thought to the immediate reality. In the following sections, I further review the impairment of solitary symbolic play among children with ASC (Section 2.2.2), the developmental difference of social symbolic play among children with and without ASC (Section 2.2.3), as well as associated intervention methods and limitations. This review provides additional theoretical background for the development of a progressive AR design approach for symbolic play enhancement in Chapter 3.

2.2.2 Solitary Symbolic Play

Numerous studies have confirmed impaired spontaneous symbolic play among children with ASC when compared to both typically developing children and mentally challenged children (Baron-Cohen, 1987; Blanc et al., 2005; Charman and Baron-Cohen, 1997; Jarrold et al., 1993; Morgan et al., 2003; Riguet et al., 1982; Rutherford and Rogers, 2003; Rutherford et al., 2007; Sigman, 1998; Sigman and Ungerer, 1984; Wulff, 1985). ASC is a neurodevelopmental condition that affects about one percent of children in the UK (Baron-Cohen et al., 2009). It is associated with impaired social communication and interaction, and restricted and repetitive behaviours, interests or activities (American Psychiatric Association, 2013). In particular, lack of symbolic play has been included in several diagnostic systems for autism such as the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2013), the Autism Diagnostic Observation Schedule (ADOS) (Lord et al., 2000) and the Childhood Autism Rating Scale (CARS) (Schopler et al., 1980).

Cognitive Explanations of Symbolic Play Impairment

There is a wealth of studies exploring the cognitive origin of the symbolic play deficit with autism and two main hypotheses have formed over the past decades (see Jarrold 2003; Rutherford and Rogers 2003 for a review). The metarepresentation theory argues that the competence of symbolic play is impaired with autism due to a fundamental deficit in forming mental representations of pretense (e.g. I pretend "the banana is a telephone") from primary representation (e.g. this is a banana) (Leslie, 1987, 1994). It is believed that pretense is an early form of mental state which requires the ability to understand one's own and other's attitudes to information. Evidence in favour of this hypothesis is based on abundant empirical results showing that children with ASC are impaired in both spontaneous symbolic play and theory of mind (e.g. Baron-Cohen, 1990; Baron-Cohen et al., 1985; Leslie and Frith, 1988).

While the metarepresentation theory provides one potential cognitive foundation of symbolic play deficit, there are other hypotheses suggesting alternative root causes. One of these hypotheses is that the cognitive competence to pretend is intact with individuals with ASC, but they have difficulty to carry out associated play actions due to (1) generativity impairment in terms of generating play ideas when external cues are absent (Boucher and Lewis, 1989; Jarrold et al., 1996; Lewis and Boucher, 1991); (2) executive function impairment which involves mental inflexibility to generate non-literal interpretation of the real world (Harris, 1993; Russell et al., 1991); and (3) lack of motivation (Koegel and Mentis, 1985). Empirical studies supporting this theory showed that children with ASC were able to perform some symbolic play under adult elicitation and instruction, although play acts were generated at a significantly slower rate and novel extensions rarely appeared (Charman and Baron-Cohen, 1997; Jarrold et al., 1996; Lewis and Boucher, 1988; Wulff, 1985). While the cognitive origin still remains inconclusive, recent studies indicate that autistic children's deficit in symbolic play is the result of heterogeneous impairments in metarepresentation, generativity, executive function, and social-emotional development (Hobson et al., 2009; Jarrold et al., 2010). In this thesis, I consider both the cognitive mechanism of pretense and the generation of associated play ideas as targets to enhance for children with ASC.

Intervention and Limitations

There is much research investigating symbolic play interventions for autistic children (see Barton and Wolery 2008 for a review). One familiar teaching method is to guide children to imitate symbolic play acts through vivo modelling (e.g. Kasari et al. 2006; Lifter et al. 2005; Sherratt 2002; Stahmer 1995; Thorp et al. 1995 or video-based modelling (e.g. D'Ateno et al. 2003). With the vivo modelling method, play therapists demonstrate solitary symbolic play acts in front of the children. For example, the therapist pushes a block into a shoebox and says: "parking the car in the garage" (Lewis and Boucher, 1988). Instead of real-time modelling, with the video-based modelling method a pre-recorded video including a sequence of modelled symbolic play acts is shown to children.

These intervention methods have several limitations. First, one major concern of modelling-based intervention is that the child might simply imitate the modelled behaviours, without actually forming intentions of play activity as typically developing children do (Luckett et al., 2007). For example, a child may simply repeat the modelled act of pushing a block into a shoebox without necessarily forming the mental representation that "the block is a car". Second, due to impaired attention and language abilities, it can be difficult for some autistic children to pay attention to the modelled play acts or understand the verbal explanation. This substantially impedes teaching efforts on the conceptualisation of symbolic thought. Third, the modelled and instructed play acts restrain children from generating original ideas on symbolic transformation and associated play acts, which affects the voluntary and flexible aspects of symbolic play. For example, children's responses under video-based modelling tend to confine to behaviours taught during the training while varied and novel behaviours are rarely seen (MacDonald et al., 2005). Fourth, accessibility of play therapies is low because one-on-one intervention can be expensive and not always available due to limited healthcare facilities.

As a result, researchers are still seeking further scaffolding methods to efficiently teach the concept of symbolic thought and increase the intrinsic motivation of autistic children to be engaged in symbolic play. I identify several advantages of using AR technologies to promote symbolic play in response to the above limitations, which are elaborated in Chapter 3.

2.2.3 Social Symbolic Play

Individual differences in social symbolic play widely exist due to atypical developmental or child-nurture factors. First, the initial difficulty in solitary symbolic play and social interaction prevents children with ASC from joining later social play with other children who acquire more sophisticated play skills during typical development (Beyer and Gammeltoft, 2000; Howlin, 1986; Jordan, 2003; Lord and Magill, 1989; Wolfberg, 2009). Second, although typically developing children are more capable of joining social symbolic play, developmental differences are often found due to social, economic and cultural factors (Baumer et al., 2005; Dockett, 1998; Fink, 1976; Levy et al., 1992; Lovinger, 1974; Odom and Strain, 1984; Rosen, 1974; Saltz et al., 1977; Smilansky, 1968). In this section, I investigate intervention methods of social symbolic play for both autistic and typically developing children as well as associated limitations.

Social symbolic play is considered a natural learning context within the zone of proximal development, which reflects a child's optimal cognitive and social abilities (Vygotsky, 1980). According to this theory, the gap between a child's optimal and current abilities can be bridged with sensitive assistance, such as interacting with more competent adults and peers. Consequently, much intervention effort has been spent to improve social symbolic play behaviour for both children with social impairments and typically developing children with and without disadvantages. For example, there are several studies investigating intervention methods to teach socially isolated or autistic children to carry out developmentally appropriate symbolic play with peers (Doctoroff, 1997; Goldstein and Cisar, 1992; MacDonald et al., 2009). Other training focuses on children with cultural and economic disadvantages (Dansky, 1980a; Lovinger, 1974; Rosen, 1974; Saltz et al., 1977; Smilansky, 1968), severely handicapped (Odom and Strain, 1984), and children without disadvantage (Baumer et al., 2005; Dockett, 1998; Fink, 1976; Levy et al., 1992).

Common intervention methods of social symbolic play include adult guidance (Dansky, 1980a; Dockett, 1998; Odom and Strain, 1984; Rosen, 1974), vivo and video modelling (Baumer et al., 2005; Levy et al., 1992; MacDonald et al., 2009; Rosen, 1974; Smilansky, 1968) and script-based enactment (Doctoroff, 1997; Goldstein and Cisar, 1992; Saltz et al., 1977). In spite of moderate effectiveness of these interventions in encouraging social symbolic play, I identify a lack of support for theory of mind development, which involves mental states of pretend roles and joint pretense, as previously discussed in Section 2.2.1.

First, simulating and responding to mental states of pretend roles such as beliefs, desires and emotional responses is largely absent in existing intervention methods. This is a rich affective experience to help children reflect thoughts and feelings from others' perspective (Irwin, 1983). In particular, several studies find that social symbolic play is related to emotion understanding as a basic feature of theory of mind (Nielsen and Dissanayake, 2000; Seja and Russ, 1999; Youngblade and Dunn, 1995). Despite the fact that symbolic play is often used as a medium to induce children with emotional and physical difficulties to communicate their own feelings in play therapies (Bernier and O'Hare, 2005), investigations of helping children proactively express and respond to emotions from another person's point of view during symbolic play has been mostly overlooked.

Second, the construction of joint pretense about roles, props and events during social symbolic play is not well supported. Joint pretense pertains to constructing shared mental representations of pretense among multiple players, so that symbolic transformations made by one player can be understood and responded to appropriately by others (Harris et al., 1993). While modelling and script based interventions provide fundamental play structures to help children initiate and maintain play activities, it does not particularly encourage them to proactively think of roles, props, and storylines. Consequently, this decreases negotiation of joint pretense, which helps young children to appreciate pretense intentions of their playmates.

In this section, I reviewed symbolic play in early childhood, including its cognitive and social importance, impairment and individual differences among autistic and typically developing children, existing intervention methods and associated limitations. This review leads to the detailed elaboration of the representational analogy between AR and symbolic play, and potential advantages of AR to support symbolic play in Chapter 3. Moreover, exploring this special childhood activity also accommodates our initial research interests about AR as addressed in Section 2.1. First, the involvement of young children with and without special needs advances our knowledge of how effectively AR can support activities of users with limited or diverse cognitive and motor abilities. Second, the dual representation nature of pretense in symbolic play provides a unique opportunity to explore the design space of AR interfaces with highly integrated representations which inherits the rich expressiveness of both physical and virtual objects in a meaningful way. Third, as a complex human behaviour involving symbolic, socio-emotional and creative mental and physical activities, symbolic play urges the development of rigorous measurements drawing on literature in multidisciplinary research fields. This extends our knowledge of evaluating the effectiveness of AR systems for complex and open-ended activities. Based on the above motivations, I develop the overall research goal of the thesis as:

Explore to what extent AR can promote cognitive and social development in symbolic play for young children with and without ASC.

2.3 AR Research with Child Users

The literature review of AR and symbolic play in the previous sections lays down the theoretical foundation for the research goal of using AR technologies to promote symbolic play for young children with and without ASC. In this section, I investigate existing research relating to the design and evaluation of AR systems for symbolic play enhancement in three perspectives: AR applications for children, technological considerations of AR to support symbolic play, and evaluation challenges. These perspectives are chosen because they help establish the detailed research context in view of the thesis research goal.

First, the review of AR applications for children informs the research focuses of AR to support childhood activities, the research gap of AR applications to enhance symbolic play and the motivation to explore this research gap. This review leads to the research question of the design space of AR systems that aims to promote symbolic play for young children.

Second, the review of technological considerations of AR to support symbolic play informs the suitability of different AR displays, as the key AR interface component, for symbolic play enhancement. Through this review, I identify that both AR displays with the see-through window or magic mirror display metaphor can support symbolic play. In view of the high accessibility of AR displays with the magic mirror metaphor and the research gap of its capacity to support physical object manipulation, I raise the research question of how usable the magic mirror display metaphor is to support symbolic play for young children.

Third, the review of existing evaluation methods applied in AR applications for children reveals the lack of rigorous evaluation methods to examine the effectiveness of AR systems that facilitate activities involving complex cognitive processes for children with diverse developmental levels. This review, therefore, leads to the third research question of exploring rigorous evaluation methods of AR in promoting symbolic play for young children with and without ASC.

2.3.1 AR Applications for Children

With the emergence of research focus on designing AR applications for special user groups (see Section 2.1.3), children are getting more and more attention as a special user group in the AR community. In this section, I first provide an overview of AR applications for children including key educational benefits of AR and representative applications. Second, I identify a lack of research focus in promoting symbolic play for young children within and beyond the AR community.

Overview of AR Application for Children

The major focus of AR applications for children is enhancing learning activities, as early childhood activities centre around cognitive and socio-emotional development (Wood and Attfield, 2005). There are several AR advantages to enhance these learning activities. First, AR enables children to get access to knowledge without switching attention between virtual and physical contexts. This accelerates the interaction and feedback processes in learning (Roschelle et al., 2000) for children who have a smaller working memory and weaker attentional control than adults (Whitebread, 2012). Second, AR supports learning knowledge in three-dimensional space, which is beneficial for young children whose spatial cognition is still under development (Cohen, 2013; Golledge et al., 1985). Third, the tangible feature of AR enables children to directly experiment with knowledge components, which is considered essential for conceptualization development (Glenberg et al., 2004; O'Malley et al., 2004), and provides playful learning experiences as it is more accessible to young children than traditional keyboard and mouse interfaces (Marshall, 2007).

Curriculum-based and play-based learning activities are the two main contexts of AR applications. The curriculum-based AR applications focus on academic subjects such as physics (Bergig et al., 2009; Buchau et al., 2009; Kaufmann and Schmalstieg, 2003; Ucelli et al., 2005), chemistry (Fjeld et al., 2007), earth and space (Kerawalla et al., 2006), physiology (Juan et al., 2008), computer science (Radu and MacIntyre, 2009), materials (Tan et al., 2008), language (Chen et al., 2007; Roberto et al., 2011), and literacy (Back et al., 2001; Grasset et al., 2008). The play-based AR applications focus on activities such as storytelling (Lee et al., 2004; Ryokai and Cassell, 1999; Sugimoto et al., 2009; Zhou et al., 2004, 2008b), social interaction (Brederode et al., 2005; Metaxas et al., 2005), and general intelligence (Andersen et al., 2004; Blanco et al., 2010). Moreover, there are emerging AR applications designed for the rehabilitation of children with diverse physical (Chau et al., 2006; Corrêa et al., 2009; Hong et al., 2010), cognitive (Richard et al., 2007) and neurodevelopmental (Farr et al., 2010) disabilities.

Applications for Symbolic Play

In spite of the importance of symbolic play and the potential of AR to enhance this activity as reviewed in Section 2.2, there has been little research effort in de-

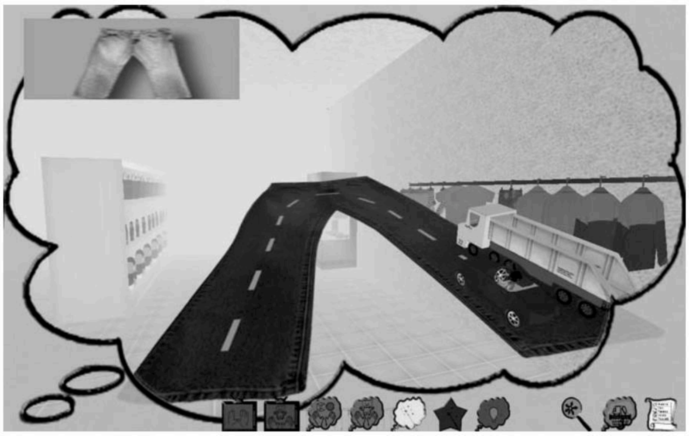
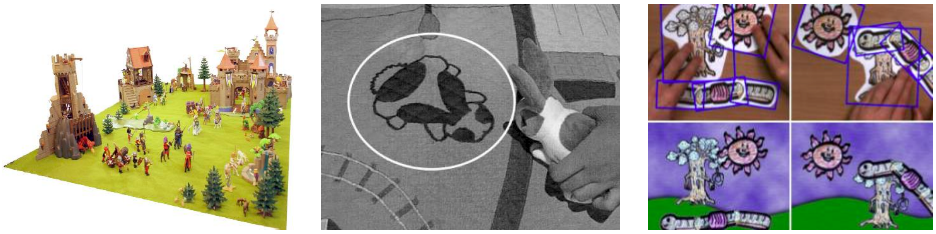


Figure 2.6: An example of symbolic transformation from a pair of trousers to a road in the VR system proposed by Herrera et al. (2008).

signing AR systems to reinforce the representational and transformational mechanism of symbolic play. In this section, I review relevant interactive systems with Virtual Reality (VR), AR or tangible user interfaces to investigate potential research focuses in approaching the thesis research goal. VR technologies generate computer-simulated environments that provide the sense of being in a real or imagined world (Steuer, 1992). Herrera et al. (2008) developed an educational VR system that shows objects seen in real life (e.g. a pair of trousers) and possible imaginary interpretations (e.g. a road) on a computer screen to teach symbolic transformation for children with ASC (Figure 2.6). This system demonstrates the advantages of visual illustrations to explain the concept of symbolic transformation to children with ASC. The VR system, however, lacks connection with the immediate environment within which children are situated. This is essential for symbolic play, during which children use one object available in the immediate environment to represent another in a non-literal way.

Unlike VR, AR and tangible user interfaces involve physical objects, thus providing a direct connection between the computer systems with the real world. Several interactive systems with AR or tangible user interfaces have been designed to assist storytelling skills, which are closely related to symbolic play. Nevertheless, these systems lack emphasis on enhancing the cognitive mechanism of symbolic play, due to the neglect of representational features of physical objects for symbolic transformation in the following two aspects.



(a) Augmented Knight's Castle (Farr et al., 2010) (b) Storymat (Ryokai and Cassell, 1999) (c) Video Puppetry (Barnes et al., 2008)

Figure 2.7: Examples of physical objects that only provide literal meaning in storytelling systems.

First, although physical objects included in some systems contribute to play-related mental representations from the immediate reality (e.g. play figures, castle, landscape), these representations remain literal and are not transformed to alternative representations in a non-literal way. Some representative applications include Augmented Knight's Castle (Farr et al., 2010), which enables the configuration of a toy castle with context aware audio narratives (Figure 2.7(a)); Storymat (Ryokai and Cassell, 1999), which encourages children to tell stories on a story mat augmented with narratives produced by previous players (Figure 2.7(b)); and Video Puppetry (Barnes et al., 2008), which allows users to record the manipulation of cut-out paper puppets on a table surface (Figure 2.7(c)).

Second, physical objects included in other systems do not contribute to mental representation involved in play activities. They simply function as tangible entities to help children interact with virtual objects more efficiently. For example, physical objects such as a sensor box, mobile phone and cubes are used to manipulate virtual characters and props in several storytelling systems (e.g. ShadowStory (Lu et al., 2011), Puppettime (Nitsche and Nayak, 2012), wIz-Quebes (Zhou et al., 2008b)) (Figure 2.8). These studies demonstrate the tangible advantages of physical objects in facilitating young children to directly interact with digital artefacts, but neglect aspects of physical objects that contribute to mental representations in cognitive processes.

The above review shows a research gap of using computer technology to enhance the cognitive mechanism of symbolic play. In particular, there is a lack of exploration of the representational and transformational aspects of physical

(a) ShadowStory (Lu et al., 2011) (b) Puppettime (Nitsche and Nayak, 2012) (c) wIz-Quebes (Zhou et al., 2008b)

Figure 2.8: Examples of physical objects that only function as tangible entities in storytelling systems.

objects among interactive systems relating to symbolic play. In this thesis, I intend to exploit the representational and tangible qualities of physical objects in an AR system to encourage meaningful and creative symbolic transformation during play. This contributes to our understanding of the AR capacity of seamless integration of physical and virtual objects to support tasks involving complex cognitive processes, as initially proposed in Section 2.1.1.

While HCI researchers often refer to developmental psychology literature with various emphases when designing interactive systems to support learning activities, there is little research on specifying primary design considerations informed by important aspects in developmental psychology literature generally shared among playful learning activities. To identify fundamental design considerations derived from developmental psychology research that guide the design of AR systems in supporting symbolic play and general play-based learning activity, I propose the first research question to be explored in Chapters 3, 5 and 6:

What are key design considerations of AR systems that promote symbolic play for young children with and without ASC?

2.3.2 AR Technological Considerations for Symbolic Play

The choice of AR display is the primary technological consideration when designing AR systems as displays determine how users perceive and interact with elements in computer systems (Sutherland, 1965). In this section, I review the suitability of different AR displays in supporting key features of symbolic play.

I identify HMD and screen-based display as the two most appropriate displays to support symbolic play. Furthermore, I investigate HMD and screen-based displays on the metaphor level in view of their familiarity to children's existing experiences. The joint concerns on ergonomic and economic issues with HMD, and potential perception issues relating to eye-hand coordination under a mirror view raise the second research question pertaining to the usability of AR displays with the magic mirror metaphor to support symbolic play.

AR Displays for Symbolic Play

In this section, I first illustrate three specific requirements associated with symbolic play activities. Based on these features, I compare the suitability of different AR displays and discuss corresponding trade-offs.

Candidate AR displays to support symbolic play have to accommodate three key features: bimanual manipulation of physical objects, flexible augmentation, and social interaction. First, it is essential for an AR system to support non-intrusive bimanual manipulation of physical objects, which is consistent with familiar play experiences in a natural setup. Second, the AR system has to support flexible augmentation on physical objects to enable visual illustration of symbolic transformations in a non-literal way. Third, the AR system has to allow children to be aware of other players' physical, social and emotional activities to ensure fluent social interaction during collaborative play. In addition, accessibility of AR displays due to cost and deployment efforts (e.g. installation) is another important factor for home and classroom usage. Based on these key requirements of AR displays to enhance symbolic play, I summarize the differences between major AR displays drawing on the previous review in Section 2.1.2. Figure 2.9 is a radar chart that illustrates the degree of support of each AR display regarding the four aspects for symbolic play enhancement. It shows that screen-based displays provide the best affordance for symbolic play enhancement as it covers the largest area in the radar chart. I compare the detailed degree of support below.

For bimanual manipulation, since screen-based, HMD and projection-based displays are hands-free, they support children to manipulate physical objects with both hands simultaneously. In contrast, handhelds require the user to hold the device with one hand, thus inevitably hindering bimanual manipulation.

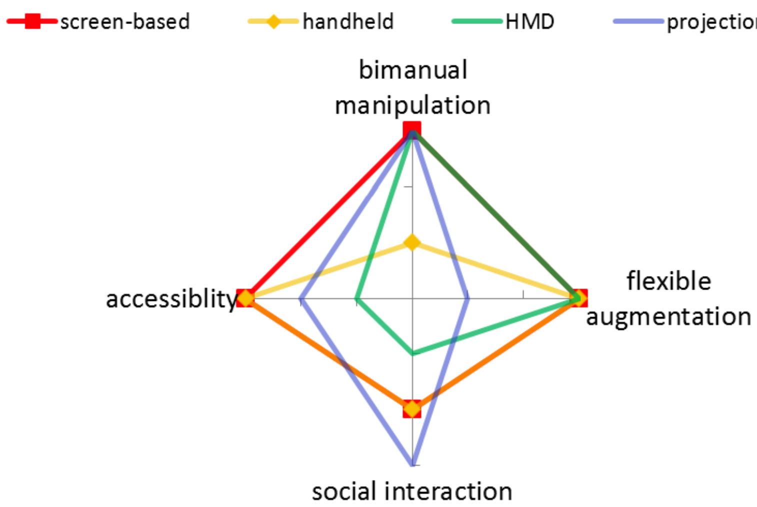


Figure 2.9: Comparison of AR displays in different aspects relating to symbolic play.

For flexible augmentation, AR systems with screen-based, handheld and HMD displays render virtual objects on a digital display separated from reality. Thus they have high flexibility in augmenting virtual contents with rich 3D qualities that are independent from the geometric features of the physical surroundings. In contrast, projection-based AR systems augment virtual contents directly on physical surfaces. This can be a potential obstacle in breaking the literal connection between the representation of reality and pretense, which is essential for symbolic transformation.

Social interaction is supported by all of the above AR displays but with wide variance in quality. On one hand projection-based displays support social interactions in a way closest to a natural setup because users do not need an extra viewing device to perceive the augmentation. HMD, on the other hand, is most intrusive for social awareness because it hinders the perception of social cues such as eye gaze and facial expression (Allison et al., 2000). For screen-based and handheld displays, the level of social awareness with other players is determined by inclusion of social cues (e.g. location and gestures of other users) within the AR view. For example, a user has to switch attention between the AR and reality view when using handhelds displays to obtain social cues. In contrast, when a screen-based display shows a mirrored view of reality including the image of all users, one can perceive social cues of others directly from the AR display.

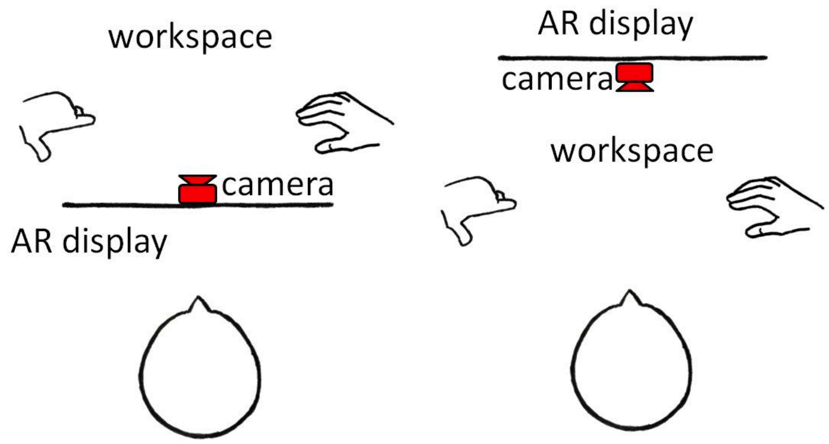
For accessibility, as discussed in Section 2.1.2, screen-based and handheld displays are the most accessible computing devices nowadays, with minimal deployment effort for AR purposes. For projection-based displays, in order to achieve high quality augmentations, multiple projectors are usually required which increases the cost and deployment complexity. The high cost and human factor issues of HMD make it difficult to be widely used in classroom and home environments.

Based on the above review, I identify a high suitability of HMD and screen-based displays to support symbolic play. Compared to HMD, screen-based displays are more cost-effective for use in classrooms and homes, with a better potential to support social interactions. On the other hand, the capacity of handheld and projection-based displays to support symbolic play is greatly limited due to shortcomings in bimanual manipulation and flexible augmentation respectively.

AR Display Metaphor

In addition to symbolic play and accessibility related factors reviewed above, the metaphor applied in AR displays is another critical consideration because it helps users interact with unfamiliar user interfaces with concepts that are already understood (Blackwell, 2006; Neale and Carroll, 1997). For example, desktop is a commonly used metaphor in modern computer systems to describe the computer monitor as a desktop on which documents and folders are placed. For AR displays, see-through window and magic mirror are the two common AR display metaphors. See-through window relates the perception of AR view to familiar experience of looking through special lenses to perceive an enhanced view of the immediate reality (e.g. magnifier and microscope). As Figure 2.10(a) illustrates, the typical setup of a see-through window follows the spatial relationship of eyes-screen-workspace, with the camera pointed in the direction of the user's gaze. On the other hand, a magic mirror relates the perception of AR view to the familiar experience of looking into a plain mirror. As Figure 2.10(b) shows, the magic mirror metaphor is implemented as eyes-workspace-screen, with the camera pointed in the direction of the user.

AR displays applying the see-through window metaphor include HMD and handheld displays, while the magic mirror mainly includes screen-based displays.



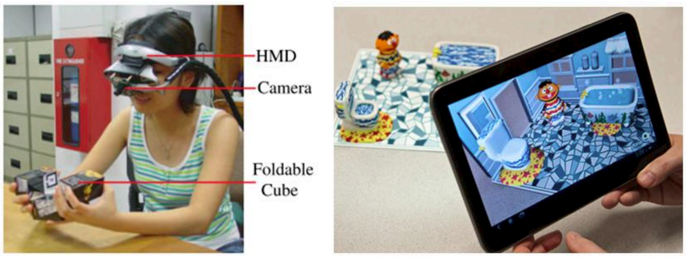
(a) See-through window (b) Magic mirror

Figure 2.10: Physical set-up of AR display metaphors.

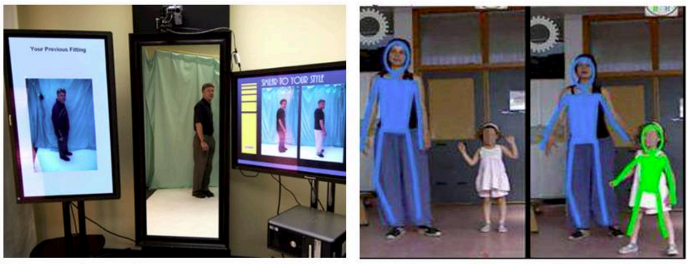
AR applications using the see-through window metaphor are widely used to facilitate professional and personal activities such as maintenance, medicine, military, tourism, and navigation (see Section 2.1.2). In contrast, there is a smaller group of AR applications with the magic mirror metaphor, which mainly focus on enhancing traditional mirror usage such as makeup (Iwabuchi et al., 2009) and fitting rooms (Zhang et al., 2008), as well as entertainment (Maes et al., 1995) and education (Blum et al., 2012; Casas et al., 2012). Some representative AR applications with the see-through window and magic mirror metaphors are shown in Figure 2.11. Despite the opposite viewpoint, displays with both the see-through window and magic mirror metaphor both simulate a first person view whether the user directly looks at the physical environment or through a mirror reflection.

Special experiences of children must be carefully considered when choosing AR display metaphors because concepts familiar to adults may be unknown to children (e.g. office) (Bruckman et al., 2002). Fortunately, children are familiar with the concept of both see-through window (e.g. Kaleidoscope, binocular) and mirror (Gallup Jr et al., 2002) from a very young age, which makes it promising to use both display metaphors to support object manipulation during symbolic play.

While bimanual manipulation of physical objects is commonly involved in AR systems applying the see-through window metaphor (e.g. repair and assembly),



(a) See-through window metaphor: Magic Story Cube (Zhou et al., 2004) (left), AR Sesame Street (Gordian, 2012) (right)



(b) Magic mirror metaphor: AR fitting room (Zhang et al., 2008) (left), Kinect-based AR System (Casas et al., 2012) (right)

Figure 2.11: Representative AR applications with the see-through window or magic mirror metaphor.

it is rarely explored with the magic mirror metaphor. This is because AR mirror interfaces mainly focus on augmenting virtual contents on the human body or interacting with virtual objects through gestures of body parts (e.g. arm, leg, whole body). Since HMD devices are too expensive to own and handheld hinders bimanual manipulation, screen-based AR displays applying the magic mirror metaphor can be an alternative to support symbolic play. Due to the lack of existing research in object manipulation under AR display with magic mirror metaphor, I am motivated to explore the second research question below, which is explored in Chapters 4, 5 and 6.

How usable is the magic mirror display metaphor in supporting object manipulation in symbolic play?

2.3.3 Usability Evaluation Challenges

As an emerging research field, AR applications for children encounter special evaluation challenges due to the complexity of learning activities and the diversity of children's abilities. In order to investigate key considerations when evaluating the effectiveness of AR systems in enhancing symbolic play, I first review primary evaluation challenges for symbolic play, and then identify insufficiencies of corresponding usability evaluations of existing AR applications for children. This motivates me to address these usability evaluation challenges in this thesis.

I recognize three main challenges when designing usability studies to evaluate the effectiveness of AR systems for symbolic play, based on the distinctive characteristics of symbolic play and the target children group. First, it is challenging to define rigorous measurements that can reliably reflect key mental processes involved in symbolic play. This is because symbolic play is an especially intricate childhood activity, as one can only interpret internal pretense intentions by observing external play behaviours (Jarrold, 2003). Second, it is challenging to design experiments for young children with ASC. This is because the performance of young children during experiments can be influenced by various factors such as attention control, ability to adapt to new environments and people, and motivation to please adults (Hanna et al., 1997). Particularly, children with ASC exhibit many difficulties in daily life, such as impaired language and joint attention, restrictive interest, and resistance to change (Schopler et al., 1980). Third, it is challenging to allow external researchers and designers to confidently apply evaluation discoveries with the sample group to the general child population. This is because children's abilities change rapidly with age and vary with gender (Bruckman et al., 2002) and there is a diverse spectrum of impairment among children with ASC due to the heterogeneous nature of autism (Johnson et al., 2007).

To investigate how well these challenges are addressed in previous studies, I examine usability evaluations among existing AR applications for children and identify two main insufficiencies: a lack of rigorous measurement methods for system effectiveness and a need for more research efforts on designing AR systems for preschool and early primary school age children.

First, there is a lack of rigorous measurement methods to evaluate system effectiveness in helping children obtain target knowledge or skills. As discussed in the survey of usability evaluation with AR applications in Section 2.1.4, rigorous measurements for the evaluation of effectiveness are largely missing among AR systems involving complex and open-ended tasks, such as education and entertainment. This is confirmed by insufficient usability evaluation among most AR applications for children reviewed in Section 2.3.1. While traditional time-error driven measures do not suit the purpose of examining complex learning and play activities, explicit evaluation methods are not yet in place. Designing AR applications for children requires cross-disciplinary knowledge and efforts. To fully confirm the effectiveness for specific developmental skills, it is essential to conduct a thorough examination involving multiple iterations and long-term evaluations on a large sample base. Therefore the quantitative effectiveness results of early evaluation become a critical discussion channel among computer scientists, educationists and therapists for future collaborative studies.

Second, more research efforts are needed for designing and reporting usability evaluations with young children. On one hand, a majority of AR applications reviewed above support educational activities for children above six years old (Andersen et al., 2004; Brederode et al., 2005; Farr et al., 2010; Fjeld et al., 2007; Kaufmann and Meyer, 2008; Kaufmann and Schmalstieg, 2003; Kerawalla et al., 2006; Lee et al., 2004; Liu et al., 2007; Radu and MacIntyre, 2009; Richard et al., 2007; Sugimoto et al., 2009; Ucelli et al., 2005), only a few studies included younger children (Chau et al., 2006; Chen et al., 2007; Ryokai and Cassell, 1999; Zhou et al., 2008b) and none were designed for children with ASC. On the other hand, there is a lack of detailed description of the user sample recruited for empirical studies. Many research efforts missed reporting complete participant information such as age and gender distribution (Back et al., 2001; Buchau et al., 2009; Corrêa et al., 2009; Metaxas et al., 2005; Tan et al., 2008; Ucelli et al., 2005), or even skipped empirical experiments with target children for various reasons (Bergig et al., 2009; Blanco et al., 2010; Hong et al., 2010; Roberto et al., 2011; Zhou et al., 2004). The ambiguity of participants' information can greatly weaken the research contribution as it makes it harder for external researchers and designers to predict candidate children populations that may benefit from these AR systems.

Addressing the above challenges can inform the evaluation of future AR and general interactive systems to support complex cognitive processes and demanding user groups. Consequently this leads to the third research question of the thesis, which is explored in Chapters 4 and 5.

What are key considerations to rigorously evaluate the effectiveness of AR systems in promoting symbolic play for young children with and without ASC?

2.4 Chapter Summary

In this chapter, I reviewed the state-of-the-art of AR and symbolic play research. This provided the theoretical foundation of this thesis and led to the overall research goal:

Explore to what extent AR can promote cognitive and social development in symbolic play for young children with and without ASC.

In view of the research goal, I reviewed the latest research of AR applications for children. I identified a research gap of using AR technologies to promote symbolic play due to the neglect of representational features of physical objects, and a lack of research on primary design considerations derived from aspects of developmental psychology literature generally shared among playful learning activities. This leads to the first research question of this thesis:

What are key design considerations of AR systems that promote symbolic play for young children with and without ASC?

I then investigated important technological considerations of AR systems for symbolic play enhancement and recognized advantages of the magic mirror AR display metaphor. The lack of knowledge in its usability capacity to support object manipulation in the AR literature leads to the second research question:

How usable is the magic mirror display metaphor in supporting object manipulation in symbolic play?

Finally, I investigated evaluation challenges for symbolic play enhancement involving young children with diverse developmental abilities, which are not fully addressed by the evaluation methods of existing AR studies with children. Consequently I raised the third research question:

What are key considerations to rigorously evaluate the effectiveness of AR systems in promoting symbolic play for young children with and without ASC?

In the remainder of the thesis, I carry out a series of theoretical and empirical studies to address the above research goal and research questions.

Chapter 3

An AR Design Approach to Enhance Symbolic Play

In the previous chapter, I reviewed AR and symbolic play as two important research contexts that indicated the foundation of a representational analogy between AR and symbolic play. Based on this analogy, I proposed the overall research goal of using AR to enhance the cognitive mechanism of symbolic play. The first step in addressing this research goal is to elaborate this representational analogy and develop it into a more specific AR approach. This AR approach is essential to guide the design of AR systems in the remainder of this thesis. The development of the AR analogy and corresponding AR approach demonstrates the importance of psychology literature in the design process of AR systems involving complex cognitive processes. The above research efforts contribute to the research question of "*What are key design considerations of AR systems that promote symbolic play for young children with and without ASC?*"

In this chapter, I investigate the detailed cognitive mechanism of key mental processes involved in symbolic play (Section 3.1). Based on this investigation, I provide a comprehensive illustration of the representational analogy between AR and symbolic play (Section 3.2), which guides the development of a three-level AR approach to progressively promote the cognitive mechanism of symbolic play in three aspects: symbolic thought, theory of mind and divergent thinking (Section 3.3).

3.1 Cognitive Mechanism of Symbolic Play

I review the detailed cognitive mechanism of symbolic play in this section as the theoretical basis of using AR to support this special play activity. First, I review general interpretations of symbolic play and identify symbolic thought, mental state and ideation as three primary features of symbolic play (Section 3.1.1). Second, I investigate the well-established "decoupler" model (Leslie, 1987) which provides the most detailed computational interpretation to date of how symbolic thought, mental states and ideation jointly constitute the mental processes of symbolic play (Section 3.1.2). Third, I elaborate the crucial contributions of symbolic thought towards theory of mind and divergent thinking development (Section 3.1.3).

3.1.1 General Interpretation of Symbolic Play

Numerous researchers in philosophy, psychology and cognitive science have attempted to explain the nature of symbolic play (see Fein, 1981 for a review). Although these explanations were made with different emphases, they reflect three general aspects of symbolic play, namely symbolic thought, mental state and ideation. I provide a concise review of established interpretations in the above aspects in this section.

First, symbolic play involves symbolic thought, which is the ability to use internal symbols and images to represent people, objects and events in reality (Piaget, 1962). Symbolic thought is the defining attribute not only for symbolic play, but also other important symbolism activities such as language and mathematics (Vygotsky, 1967). It is described as a series of transformational behaviors when children transform the mental representation of one object or situation to another (Fein, 1975). The transformational behaviour is further elaborated into three forms, namely object substitution, attribution of false or absent property and presence of imaginary objects (Leslie, 1987). In particular, dual representation is the distinguishing characteristic of symbolic thought. For example, Piaget (1962) argued that the mental image of an absent object assimilated to the mental representation of a present object is evoked during symbolic play. Similarly, it is suggested that double knowledge of the original mental representation of one object and its expressed representation in substitution has to be maintained simultaneously to avoid confusion in symbolic play (McCune-Nicolich, 1981).

Second, symbolic play involves mental states that are essential to understand intentions and behaviours of oneself and others (Premack and Woodruff, 1978). This is because pretense in symbolic play is a particular mental state that shares similar characteristics with other mental states such as belief and desire (Leslie, 1987). During social symbolic play, children have to appreciate that playmates may hold different pretense representations than their own. Thus they must develop effective communication skills to construct joint pretense (Whitebread and O'Sullivan, 2012). Moreover, as symbolic play gradually shifts from self-directed (e.g. put an empty cup toward one's mouth) to other-directed play (e.g. put an empty cup towards a doll's mouth) (Fein, 1981), children start engaging more and more in role play, during which they simulate mental states such as belief, desire and emotion response from a third person's perspective (Lillard, 2001a). Therefore the mental state aspect of symbolic play leads to theory of mind, which is a critical ability developed in later childhood.

Third, symbolic play involves ideation, which is the creative process of forming ideas (Runco, 1991). According to Piaget (1962), symbolic play is considered as a "source of creative imagination" and there are two main ideational processes involved namely symbolic thought and play idea. The generation of symbolic thought reflects the flexibility in transformational activities in play (e.g. a shell is substituted by a cat), while the generation of play ideas reflects the ability of creating imaginary episodes by combining unrelated symbols (e.g. put a leaf in a box as if dropping a letter in a post-box). Both ideational processes help children to form unusual associations among objects and situations, which contribute to divergent thinking, an important ability of generating diverse ideas (Clark et al., 1989; Dansky, 1980b; Moran et al., 1984).

3.1.2 Computational Interpretation of Symbolic Play

The review in the previous section offers a fundamental understanding of the three key cognitive aspects of symbolic play. In order to build the AR analogy that will be elaborated in Section 3.2, it is necessary to explain the "decoupler" model (Leslie, 1987), which provides a computational account of how these key aspects jointly constitute the mental processes of symbolic play. This in turn underpins the progressive AR design approach developed in Section 3.3.

The Computational Theory of Mind

The computational theory of mind is prerequisite knowledge for the "decoupler" model. This theory uses the analogy of information processing in computational systems to explain how the human mind works (Pitt, 2013). It states that mental process contains the occurrence, transformation and storage of mental representations, which are the fundamental information units manipulated in the human mind. As a common mental process, humans project different propositional attitudes towards mental representations. Such propositional attitudes are also known as mental states which include thoughts, beliefs, desires, perceptions, imaginings and so forth. Below is an example illustrating how the mental process of "believe" is constructed:

Eileen <u>believes</u> that <u>sugar tastes sweet</u>

In this mental process, the mental state is "believe" and the mental representation that the mental state refers to is "sugar tastes sweet". Leslie (1987) identified a high isomorphism between pretense and mental state expression in language. He used the term "metarepresentation" in the following form to describe the second order mental representation derived from primary mental representation of reality:

Agent - Informational Relation - "Expression"

The example below demonstrates a metarepresentation constructed in symbolic play:

Eileen <u>pretends</u> that <u>this banana is a telephone</u>

In this example, "pretend" is the mental state and the mental representation is "this banana is a telephone". The major difference between "pretend" and "believe" is that the mental representation associated with "pretend" involves non-literal mental representations that differ from reality, while "believe" requires the subject to consider the associated mental representation "to be or have been the case" (Gendler, 2013). The non-literal representation derives from the primary representation of the real situation but is distorted to accommodate the subject's intention.

The "Decoupler" Model

The "decoupler" model outlines the cognitive mechanism of how primary representation is decoupled from the context of reality to form the corresponding

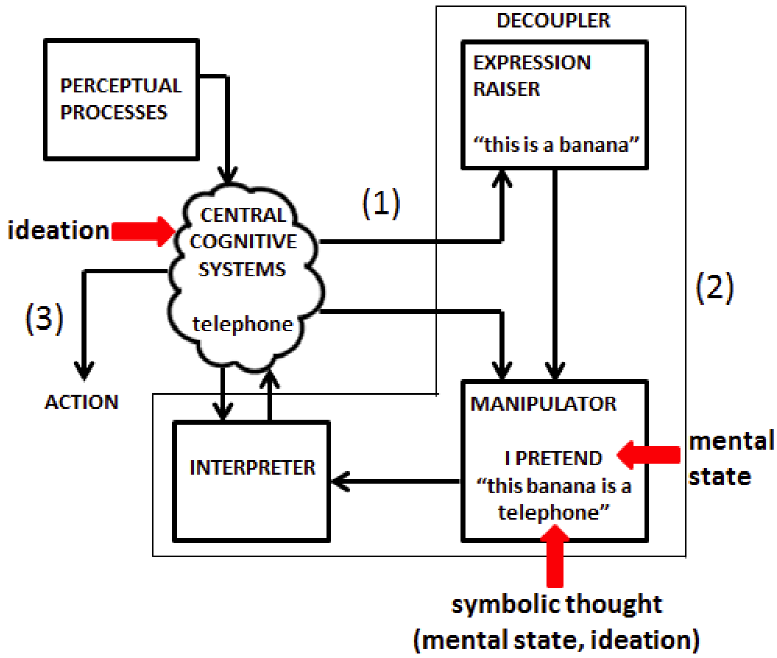


Figure 3.1: A redraw of the "decoupler" model (Leslie, 1987).

metarepresentation. It also locates this transformational process in the cognitive flow from perception to action, which informs processes relating to symbolic thought, mental state and ideation of play ideas.

The "decoupler" model is illustrated in Figure 3.1. The flow of mental processes to complete a pretend act involves three major steps: (1) the "central cognitive systems" send the primary representation (e.g. "banana") to the "decoupler"; (2) the "decoupler" generates a decoupled copy of the primary representation, namely the metarepresentation (e.g. I pretend "this banana is a telephone") and sends it back to the "central cognitive systems"; (3) the "central cognitive systems" generate play ideas (e.g. talk to the telephone) and convert them into perceivable play actions based on general knowledge (***ideation***). The metarepresentation includes the ***mental state*** of "pretend" and the ***symbolic thought*** in the form of mental representation ("this banana is a telephone"). In particular, ***symbolic thought*** also involves ***ideation*** and ***mental state*** when it comes to the formation of symbolic thoughts and mental states of pretend roles as discussed in Section 3.1.1.

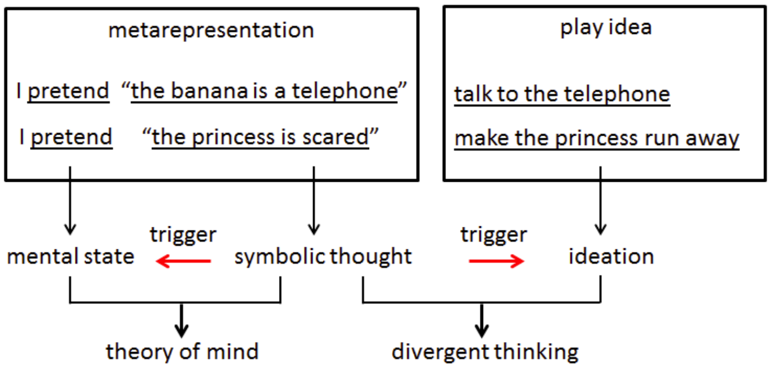


Figure 3.2: The illustration of the leading role of symbolic thought towards theory of mind and divergent thinking.

Although the cognitive mechanism of pretense described by the "decoupler" model is well perceived, children may not understand that "pretend" is a representational mental state until later stages of symbolic play when they start to reason about pretense intentions of playmates (Friedman and Leslie, 2007; German and Leslie, 2001; Lillard, 1993b; Perner, 1991). In this thesis, I concur with the notion that there is a gradual increase of the ability to understand the cognitive mechanism of pretense as symbolic play shifts from solitary to social (Jarrold et al., 1994; Lillard, 2001a).

3.1.3 Importance of Symbolic Thought

The "decoupler" model illustrated in the previous section locates symbolic thought, mental state, and ideation in the mental processes of pretense in symbolic play. In this section, I elaborate the leading role of symbolic thought towards theory of mind and divergent thinking development. Figure 3.2 shows how symbolic thought can potentially trigger the mental processes of theory of mind and divergent thinking.

First, symbolic thought is the potential source for theory of mind. As reviewed in Section 3.1.1, in order to understand the non-literal transformation made by a playmate, a child has to realize that the playmate has his/her own pretense intention associated with objects and situations. In addition, to attribute a different mental state to a pretend character, a child has to understand that the character has different beliefs and desires than him/her and reason about the mental state change from a third person perspective. Second, symbolic thought is heavily involved in the generation of divergent play ideas. This is because symbolic thought provides an “initial premise” (Nichols and Stich, 2000) that can evoke a sequence of play ideas and corresponding play behaviours. For example, with the symbolic thought of “the banana is a telephone”, a person will put the banana close to one’s ear and talk to it. Moreover, as discussed in the previous section, the formation of symbolic thought itself requires children to generate imaginary associations with objects and situations based on general knowledge within the “decoupler” model.

In summary, symbolic thought resides at the core of symbolic play which facilitates theory of mind and divergent thinking processes. Recognising this, in the next section I focus on elaborating the representational analogy between AR and symbolic thought in symbolic play, which lays the foundation of using AR to enhance symbolic play in this thesis.

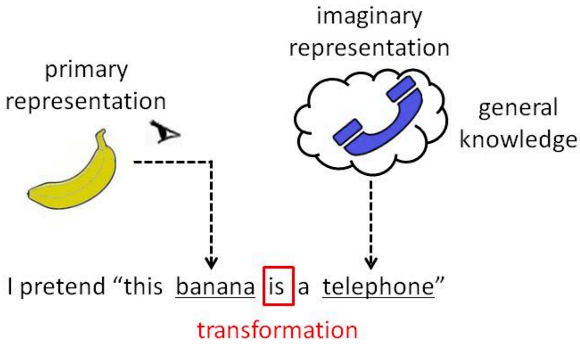
3.2 Analogy between AR and Symbolic Play

In Section 2.2.1, I briefly proposed an analogy between AR and symbolic play because both AR and symbolic play involve projecting alternative interpretations on objects and situations in reality. In this section, I provide an in-depth discussion of the analogy based on the computational theory of symbolic play reviewed in Section 3.1. This analogy provides the foundation towards an AR approach to facilitate and advance cognitive processes of symbolic play by externalizing the otherwise “opaque” symbolic thought via visual illustration.

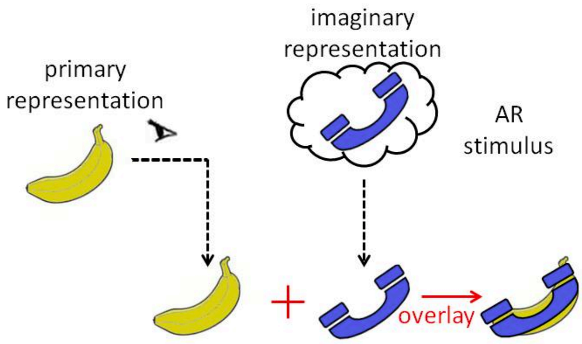
3.2.1 Visualising Symbolic Thought

I propose that AR can help visually illustrate the mental process of symbolic thought, which is characterized with the dual representation and transformation features of symbolic play. To elaborate this proposal, a concrete example is given to illustrate the formation of symbolic thought in the usual pretense scenario and in the alternative AR scenario.

Figure 3.3(a) shows how symbolic thought is formed in the metarepresentation “I pretend this banana is a telephone” based on the “decoupler” model discussed in Section 3.1. A child sees a real banana, which is raised to be the



(a) An example of symbolic thought in mind



(b) An example of symbolic thought presented by AR

Figure 3.3: An illustration of the representational analogy between symbolic thought and AR.

primary representation. Based on general knowledge stored in the "central cognitive systems", an imaginary representation, "telephone", is conceived. Once the dual representations are formed, the primary representation is then transformed to the imaginary representation, which completes the symbolic thought of "this banana is a telephone". Alternatively, Figure 3.3(b) shows how AR illustrates the same symbolic thought. The analogy of AR and symbolic thought lies in two aspects: dual representation and transformation. First, the primary representation is obtained from reality in the same way as perceived by the child. Instead of obtaining the imaginary representation from general knowledge, the imaginary representation is suggested by AR as a visual stimulus. Second, AR

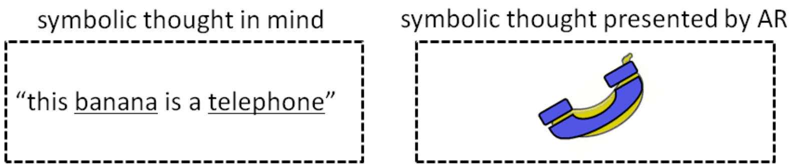


Figure 3.4: Symbolic thought in mind vs. symbolic thought presented by AR visualisation.

makes the imaginary representation overlay and follow the primary representation as it moves to illustrate the transformational process from primary to imaginary representations. As Figure 3.4 illustrates, the symbolic thought formed through the example process is "this banana is a telephone". AR externalizes this symbolic thought by superimposing the image of a telephone on the image of the real banana (Figure 3.4).

3.2.2 AR as An External Cognitive Structure

I propose that AR can function as an external structure to support the cognitive processes involved in symbolic play according to the theoretical background of extended mind and external cognition. Externalism in the philosophy of mind essentially argues that the human mind extends beyond our skull into body and world (Haugeland, 1993; Varela et al., 1993). The human cognition system is thus considered as a joint constitution of our mind and the real world. The extended mind model furthered the externalism theory by emphasizing the "active role of the environment in driving cognitive processes" (Clark and Chalmers, 1998, p. 7). Similar to extended mind, the embodied cognition theory also emphasizes that human cognition is largely situated in the immediate environment and shaped by the way people interact and manipulate external props (Anderson, 2003; Dourish, 2004). With the rapid development of computer technologies in the past decades, digital artefacts have penetrated into the fabric of human activities and are widely used as enhanced media to support cognitive activities such as study, work and play (Scaife and Rogers, 1996; Singer and Singer, 2009). As Scaife and Rogers (1996) suggested, novel forms of representation engendered by emerging computer technologies are capable of enhancing internal cognitive mechanisms in ways that are not available with traditional media. They defined external cognition as "the cognitive process involved when interacting with graphical representations" and urged researchers to consciously exploit the design space of graphical representations that support effective external cognition for learning and other related topics.

In line with the extended mind and external cognition theories, I argue that the proposed AR analogy is promising to enhance key cognitive processes involved in symbolic play in the following two aspects. The advantages of using AR to enhance symbolic play in response to major limitations of conventional intervention methods (see Section 2.2) are discussed correspondingly.

First, AR can be used as an external structure to help children to understand the cognitive mechanism of symbolic thought in play. One of the hypotheses to explain why children with ASC rarely carry out spontaneous symbolic play is that their metarepresentation ability experiences delayed development (see Section 2.2.2). AR enables children to learn the representational and transformational nature of symbolic thought through visual illustrations. This visual illustration may providealternative prompts in addition to physical modelling and verbal instruction by externalizing mental images upon the immediate environment. This approach is promising to accommodate the visual learning style associated with autism (Quill, 1997) and eliminate potential learning obstacles due to language deficits. Moreover, AR enables children to generate symbolic transformations and practice associated play ideas through physical manipulation of the otherwise invisible imaginary representations. Physical manipulation is considered essential to accelerate children's development of representational and social cognition (Flavell, 1963) and "leads to the appreciation of symbols in pretense" (Lillard, 2008).

Second, AR can be used as an external structure to reinforce divergent thinking and theory of mind during play as symbolic thought lies at the heart of these two cognitive processes. To begin with, AR provides the visualization of imaginary representation as an "initial premise" (Nichols and Stich, 2000) to help children generate open-ended play ideas without following explicit physical and verbal instructions. Such instructions may largely confine children's spontaneity and novelty in symbolic play. In addition, AR supports children to come up with symbolic transformations by their own choice, which are no longer pre-defined as in modelling and script-based interventions. Consequently it encourages children to explain their pretense ideas upon creation in order to maintain agreement of joint pretense with other players. Moreover, AR can promote children's ability

Stimulus	Primary Representation	Imaginary Representation	Transformation	Play Idea
Level-1	yes	yes	yes	to be made
Level-2	yes	yes	to be made	to be made
Level-3	yes	to be made	to be made	to be made

Table 3.1: Elements of symbolic play given in each stimulus level.

to reason and respond to mental states of pretend roles, which has been mostly overlook in previous interventions (see Section 2.2.3). With careful design, AR can provide a fun and enjoyable social play experience that makes it easier for typically developing children to support peers with special needs, which is difficult in conventional trainings due to the children's young age (Goldstein and Cisar, 1992; McConnell, 2002; Zercher et al., 2001).

3.3 An AR Approach to Support Symbolic Play

3.3.1 Three-level AR Approach

The analogy of AR and symbolic thought elaborated in the previous section suggests several opportunities for using AR to enhance symbolic play. In this section, I develop a progressive AR design approach with three levels of stimulus to progressively promote symbolic play in terms of symbolic thought, theory of mind and divergent thinking. This approach provides essential strategies that guide the design of the two AR systems in this thesis which are described in Chapters 5 and 6.

The core strategy is for AR to facilitate a progressively higher levels of elicitation of mental efforts to generate symbolic thought during play for children in different developmental stages. The cognitive structure of each level is described in Table 3.1. Elements of symbolic play marked as "yes" are provided by the AR system. Those marked as "to be made" are expected to be generated by children. I use the examples in Table 3.2 to demonstrate the intention that each AR stimulus level aims to communicate to children.

Stimulus	Intention of AR stimulus	
Level-1	Pretend “this banana is a telephone”.	What play ideas can you think of?
Level-2	Which of these items do you want to pretend this banana to be?	
Level-3	What do you want to pretend this banana to be?	

Table 3.2: Example of the intention of each AR stimulus level.

Level-1

The goal of level-1 stimulus is to illustrate the mental process of symbolic thought and encourage the generation of associated play ideas in a divergent way. By presenting a pre-defined set of symbolic thoughts with all three elements including primary representation, imaginary representation and transformation, the AR structure is expected to (1) visually illustrate the formation of ***symbolic thought***; and (2) encourage ***divergent thinking*** in generating play ideas by minimizing the mental effort of conceiving symbolic thought and providing additional visual facilitations to evoke general knowledge associated with the indicated symbolic thought (e.g. help children to associate the play idea of “train moves along the train track” with the symbolic thought “this block is a train” by augmenting a virtual train track in the physical environment). The level-1 stimulus is applied in the design of the AR system in Chapter 5.

Level-2

The goal of level-2 stimulus is to facilitate the formation of symbolic thought and promote symbolic transformation relating to theory of mind. By providing children with a set of candidate imaginary representations and helping them to form intentional transformations according to the spontaneous play context, the AR structure is expected to: (1) familiarize children with the transformation mechanism of ***symbolic thought*** by supporting them to manipulate symbols in a tangible manner; (2) facilitate ***theory of mind*** development by supporting children to transform mental states of pretend roles, reason and respond to the mental state change according to the immediate play context. The level-2 stimulus is applied in the design of the AR system in Chapter 6.

Level-3

The goal of level-3 stimulus is to further children's abilities in symbolic thought, divergent thinking and theory of mind. To achieve this goal, instead of providing imaginary representation candidates with definite meanings, AR provides stimuli with more open-ended meanings to encourage children to independently construct imaginary representations and associated transformations. The high degree of open-endedness in this level potentially allows AR to: (1) advance ***symbolic thought*** and ***divergent thinking*** abilities by helping children to conceive imaginary representations and relate these to primary representations via transformation in a more open-ended and independent way; (2) reinforce ***theory of mind*** development because children have to effectively communicate about the open-ended symbolic thought conceived during play among playmates in order to construct and respond to shared symbolic thoughts appropriately to avoid misunderstanding during play. The level-3 stimulus is applied in the design of the AR system in Chapter 6.

3.3.2 Design Reflections

The three-level AR approach reflects the primary design strategy of AR systems to support play activities for children with diverse developmental abilities in two main aspects: cognitive and developmental. First, the cognitive mechanism of symbolic play informs the analogy between AR and symbolic thought, and the causal relationship between symbolic thought and both theory of mind and divergent thinking. This indicates that an in-depth review of the cognitive mechanism of specific play activities (e.g. the "decoupler" model) is essential to help identify the special strength of AR to support certain cognitive processes. In addition, such review enables researchers to understand the connection of the core cognitive processes to other important developmental abilities associated with the play activity, thus unfolding potential opportunities to maximize the effectiveness of AR to promote the play activity. Second, AR approaches to enhance cognitive abilities of young children have to be designed through the lens of gradual development in early childhood. As reviewed in Section 2.2, there is a common developmental difference among young children in symbolic play due to atypical developmental and nurture factors. This reflects a general variation of individuals' cognitive abilities around the optimal level within a certain age range, therefore requires a sustainable design strategy to accommodate needs of children with diverse developmental abilities. The progressive increase of mental effort to conceive symbolic thought implied by the three-level AR approach illustrates a potential strategy to support cognitive processes of children with diverse abilities in the zone of proximal development. Moreover, the increase of mental effort results from an escalating open-endedness of the user's manipulations of representational and transformational elements involved in symbolic thought, which complies with open-ended learning processes by allowing children to explore and manipulate concepts (Land, 2000).

3.4 Summary

This chapter addressed the core AR approach that guides the design of the two AR systems in Chapters 5 and 6 in three steps. First, I discussed the cognitive mechanism of symbolic play in detail, which provided the representational foundation upon which the AR analogy is based. Second, I elaborated the analogy between AR and symbolic play, in particular symbolic thought. This analogy specified the essentials of using AR to promote symbolic play. I explicated AR as an external structure that can potentially influence cognitive processes according to the extended mind and external cognition theories. Third, I developed the AR analogy into a three-level AR design approach to enhance symbolic thought, theory of mind and divergent thinking in symbolic play. Design reflections associated with the AR approach were elaborated. Different aspects of the AR approach are applied in the design of the two AR systems, which are presented in detail in Chapters 5 and 6.

Chapter 4

A Preparatory Usability Study of AR Magic Mirror

4.1 Introduction

In this chapter, I present a preparatory study to explore the usability of AR displays with the magic mirror metaphor, also referred to as "AR magic mirror" in this thesis, to support bimanual manipulation of physical objects. This study was conducted in parallel with the investigation of the AR design approach to enhance symbolic play presented in Chapter 3. As an initial investigation of usability of AR magic mirror, this study focuses on obtaining preliminary knowledge of how capable general adult users are to adapt their visuomotor skills of physical object manipulation to the AR magic mirror view. I decided to save the participation of child users, who are much more difficult to recruit than adult users, for formal studies conducted in later chapters. Findings of this study reveal future opportunities of AR systems with the magic mirror display metaphor in supporting physical object manipulation. In particular, these findings are helpful to inform the design of the two AR systems developed in Chapters 5 and 6 for symbolic play enhancement.

As discussed in Section 2.3.2, there are two alternative display metaphors for AR screens: either a see-through window or a magic mirror, depending on whether the setup is eye-screen-space with the camera pointed in the direction of the user's gaze, or eye-space-screen with the camera pointed towards the user. Although both screen-based AR displays with the magic mirror metaphor and HMDs with the see-through window metaphor support the core features of symbolic play enhancement, the former is more accessible for classroom and home usage. So far most AR applications involving interaction with physical objects apply the see-through window metaphor, with the magic mirror metaphor a largely unexplored design space. As a result, little is known about the usability of AR magic mirror displays to support bimanual manipulation of physical objects.

It may be that this gap is due to the conceptual bias assuming poorer eye-hand coordination due to mirror reversal. Several theories, however, suggest a high potential for users being able to adapt object manipulation skills to a magic mirror view, which resembles the view of a plane mirror. For example, the perception adaptation theory suggests that the human brain can effectively adapt to altered visual fields after sufficient exposure (Stratton, 1897). Research also shows children as young as four years old can obtain mirror tracing skills, which requires the subject to achieve various visuomotor tasks when perceiving the actions from a mirror (Gabrieli et al., 1993; Ketterlinus, 1931).

As a preparatory usability study to answer the above question, I designed a novel experiment to compare participants' performance when following object rotation cues between AR displays with the see-through window and magic mirror metaphors. I use user performance of a see-through window as a benchmark to inform users' optimal bimanual manipulation performance with an AR system. The rotation task is chosen with reference to the well-recognised mental rotation task (Shepard and Metzler, 1971), which considers rotation as a demanding visuospatial process that directly guides one's motor responses during object manipulation.

The findings reported at the end of this chapter are that participants' overall performance under the magic mirror view was comparable to the see-through view, which indicates that the AR magic mirror can be a promising alternative to the see-through window display to support symbolic play enhancement, as well as general AR applications which involve moderately complex three-dimensional manipulations with physical objects. Furthermore, participants tended to prefer the first viewing condition they encountered in the experiment, regardless of whether that was magic mirror or see-through. This suggests that it is comparably easy for a user to adapt eye-hand coordination in both see-through window and magic mirror views.

The remainder of the chapter is structured as follows. In Section 4.2, I provide a review of research in the magic mirror display metaphor, mirror reversal and related AR usability studies. In Section 4.3, I present the detailed methods of the usability study and report the study results in Section 4.4. This is followed by a discussion of the implications and limitations of the study in Section 4.5. Finally, I summarize discoveries of the usability study in terms of designing the AR magic mirror to support physical object manipulation.

4.2 Related Work

See-through window and magic mirror are AR display metaphors that simulate two different types of first person view. The see-through window provides an egocentric view as if the user is directly looking at the workspace. The magic mirror, on the other hand, provides a mirror view as if the user is looking at the workspace in a mirror. As discussed in Section 2.3.2, the see-through window setup usually includes a HMD or handheld display with a rear camera, and is commonly used in task-support AR applications (e.g. maintenance, assembly) when a user manipulates physical objects under visual instructions registered in the real world. The magic mirror setup includes a desktop monitor, handheld display with frontal camera, large projection display or digitalized semi-transparent mirror (Sato et al., 2009). It is mostly used in scenarios when a user either perceives virtual objects superimposed directly on his/her body or interacts with virtual objects with body parts (e.g. Kinect games).

In the following sections, I first investigate the magic mirror metaphor as applied in existing AR applications and identify its lack of usage for physical object manipulation. I then explore the theoretical background of mirror reversal and exclude it as a potential obstacle for users to adapt their eye-hand coordination. Last, I look into usability issues of monitor-based AR displays relating to mirror reversal and recognize a research gap to be tackled in this study.

4.2.1 Magic Mirror Display Metaphor

A mirror is an everyday display technology that faithfully reflects our appearance and behaviour. Besides conventional scenarios to observe one's appearance, mirrors are also used as apparatus to teach new motor skills for people with neuropsychological conditions (e.g. Alzheimer's (Gabrieli et al., 1993), phantom limb

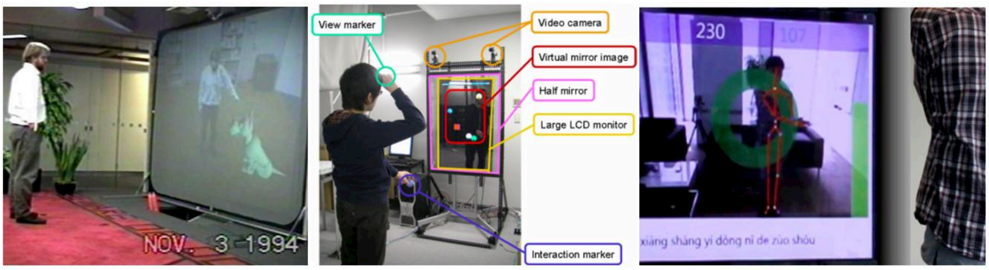


Figure 4.1: Example of AR magic mirror applications that apply full-body interaction (from left to right): ALIVE system (Maes et al., 1995), MR-mirror (Sato et al., 2009), SpatialEase (Edge et al., 2013).

pain (Ramachandran et al., 1995)) and motor deficits (e.g. stroke (Yavuzer et al., 2008)). The magic mirror display metaphor takes advantage of people's familiarity with mirror perception by providing a reflected view of reality including one's own image. It is first described by Maes et al. (1995) in the ALIVE system, in which a user observes his/her own image and autonomous virtual agents from a real-time video feed projected on a large display. The users use full body gestures to interact with these virtual agents (Figure 4.1 (left)).

Several AR systems since have used a similar magic mirror metaphor to support users' interaction with virtual augmentations through physical movements and full-body gestures (e.g. Augmented Man (Stricker et al., 2000), Invisible Person (Psik et al., 2003), MR-mirror (Sato et al., 2009), EyePet (Sony, 2009), Kinect Party (Microsoft, 2012)) or produce certain body actions under the guidance of virtual augmentations (e.g. SpatialEase (Edge et al., 2013)). Figure 4.1 shows a sample of the above mentioned applications. In these systems, the image of one's body functions as the main input method for interacting with virtual objects or following virtual guidance, as well as a closed-loop visual feedback to enable monitoring of one's own actions in real-time.

Another group of AR systems with the magic mirror metaphor are designed to augment user facial and body appearance (Figure 4.2). For example, the i-mirror system alters a user's appearance to seem older or younger (Ushida et al., 2002). The ChroMirror system allows users to observe the clothes they are wearing in different colours (Cheng et al., 2008). The Smart Makeup Mirror provides a digital dressing table that facilitates a user to apply makeup (Iwabuchi et al., 2009).

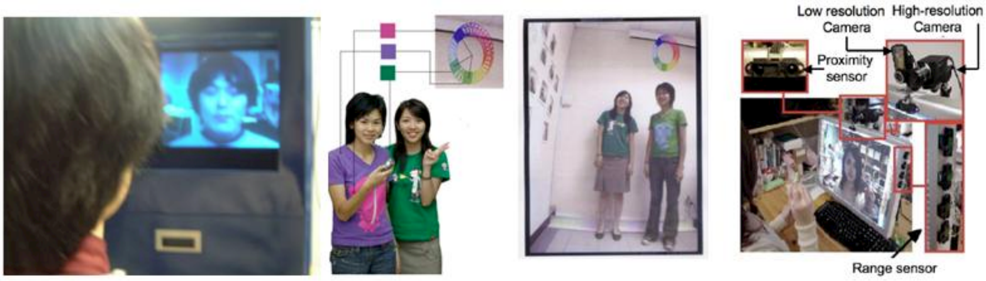


Figure 4.2: Example of AR magic mirror applications that enhance user's appearance (from left to right): i-mirror (Ushida et al., 2002), ChroMirror (Cheng et al., 2008), Smart Makeup Mirror (Iwabuchi et al., 2009).

There are several advantages of the AR magic mirror in supporting symbolic play, as discussed in Section 2.3.2. First, the AR magic mirror allows users to manipulate physical objects with both hands. This is essential for the mental processes of symbolic transformation in play and maintains a strong connection to natural play experiences. Second, the AR magic mirror allows a user to perceive social cues of other playmates during play (e.g. body location, gesture, eye gaze and facial expression) by including the image of other players. Third, the image of one's own body provides a strong sense of presence, which refers to the observer's feeling of being present within the display scene (Agamanolis, 2003; Kim et al., 2004; Milgram and Kishino, 1994; Morikawa and Maesako, 1998). Presence is believed to have a strong correlation with agency, which refers to a person's sense of being in charge of their actions and responsible for the consequences (Coyle et al., 2012; Haggard and Tsakiris, 2009; Shneiderman and Plaisant, 1992; Synofzik et al., 2008). Sense of agency is especially beneficial for children with ASC, who are often found to have a lack of agency, which causes impaired self-awareness and theory of mind (Leslie, 1994, 1995; Russell, 1997; Russell and Jarrold, 1999; Williams, 2010).

Despite the above advantages, there are far fewer AR applications that apply magic mirror than see-through window metaphors. As these examples show, AR applications with the magic mirror metaphor mainly focus on supporting full-body interaction with virtual objects or enhancing the user's appearance, instead of manipulating physical objects from the immediate environment. Since physical object manipulation is essential for symbolic play, a critical question for this thesis is the extent to which users can manipulate physical objects with an AR magic mirror. One of the major concerns is the impact of eye-hand coordination introduced by mirror reversal under the magic mirror view. In the next section, I investigate eye-hand coordination adaptation under the condition of a mirrored view and related implications for the AR magic mirror.

4.2.2 Eye-hand Coordination under the Mirror View

Eye-hand coordination is a special visuomotor skill that refers to using visual input to guide hand actions for object manipulation (Johansson et al., 2001). It is a fundamental mechanism to perform tasks in real life from simply grasping a tea cup to complex surgery. In particular, eye-hand coordination is an important psychological aspect that affects efficiency of user interaction with computer interfaces (Olson and Olson, 2003). When a user interacts with a conventional computer interface via input devices such as a mouse or joystick, he or she has to map actions in the real world coordinate system to the coordinate system of the virtual workspace. During this process, eye-hand coordination allows the user to learn and master such coordinate mapping. Similarly, when a user manipulates physical objects through an AR display, he or she has to map actions in the real world coordinate system to the AR coordinate system. The view provided by a see-through window resembles an egocentric view of the user's usual view (Milgram and Kishino, 1994), with slight alterations due to imperfect matching of viewpoint between human eyes and the capture device (Biocca and Rolland, 1998). Therefore, minimal adaptation for eye-hand coordination is required for object manipulation in a see-through window view. On the other hand, the view provided by a magic mirror resembles a mirrored view when a user looks into a mirror.

The most salient phenomenon involved in visual perception via a mirror is mirror reversal. The common sense explanation is that a mirror image reverses the left and right of a real object (Gregory, 1987). A more precise description is that "a mirror optically reverses the axis perpendicular to its surface" (Ittelson et al., 1991). When people perceive and monitor their actions from a mirror, they experience a perceptual transition from the mirror view to the physical view (Magid, 1986). Therefore a user's ability to adjust object manipulation under a magic mirror display largely depends on his or her ability to learn motor skills in a mirror situation.

Learning new eye-hand coordination skills under a mirror view can be explained according to the perception adaptation theory (Harris, 1965; Kohler, 1963; Stratton, 1897). Extensive experiments show that the human brain can effectively account for optically distorted visual fields and allow individuals to adapt to such change over a period of exposure. For example, Stratton (1897) detailed a self-report of his adaptation to a vertically inverted visual field over a period of eight days. Kohler (1963) in a later study observed subjects wearing left-right reversing goggles and reported their behavior and vision reoriented after several weeks' time. Furthermore, mirror tracing is a common visuomotor task which uses a mirror as an optical device in training people to learn motor skills (e.g. drawing or object moving) involving eye-hand coordination in an altered vision condition (Cavaco et al., 2004; Gabrieli et al., 1993). The results of a series of studies investigating the ability of preschool children to adapt to mirror reversal show a definite learning ability of young children as young as four years old to adjust eye-hand coordinates in a mirror condition (Ketterlinus, 1931).

The above studies support the feasibility of using the AR magic mirror to support tasks involving physical object manipulation in spite of mirror reversal. In addition, there is another body of research investigating people's general understanding on the correspondence of movement between an object and its mirror reflection (Bertamini et al., 2003; Croucher et al., 2002; Hecht et al., 2005; Savardi et al., 2010), which provide a useful reference when designing an AR magic mirror to support object manipulation. One recent discovery is that participants believe reflections move the same way when they see movements approximately parallel to the mirror (0°-22.5°), but the opposite when approximately orthogonal (67.5°-90°) (Savardi et al., 2010). This result indicates that an AR magic mirror may effectively control the mirror reversal effect when the user moves the physical object along a plane roughly aligned with the mirror-analogue screen.

In sum, greater effort is needed to adapt eye-hand coordination to a magic mirror than a see-through window when interacting with physical objects in an AR environment due to mirror reversal. Nevertheless, empirical studies in perceptual adaptation indicate that such effort is achievable even for very young children, who are less experienced with motor adaptations to objects seen in a mirror. This theoretical background supports my initial motivation to examine the feasibility of using the magic mirror AR display to support object manipulation in symbolic play. In the next section, I investigate general usability issues

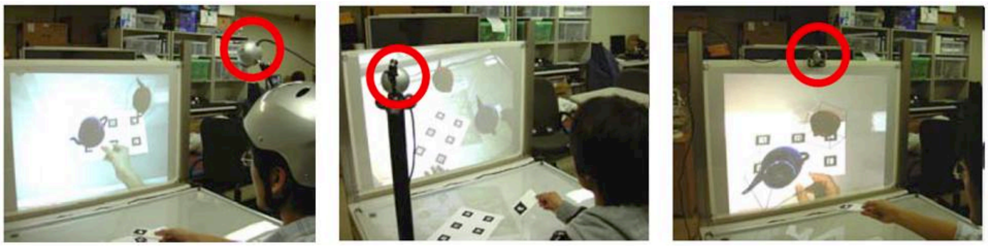


Figure 4.3: Experiment apparatus of Jeon et al. (2006)'s study. The camera is fixed (from left to right) on the user's head, behind the user, on top of the monitor.

relating to mirror reversal reported in existing AR research.

4.2.3 AR Usability due to Mirror Reversal

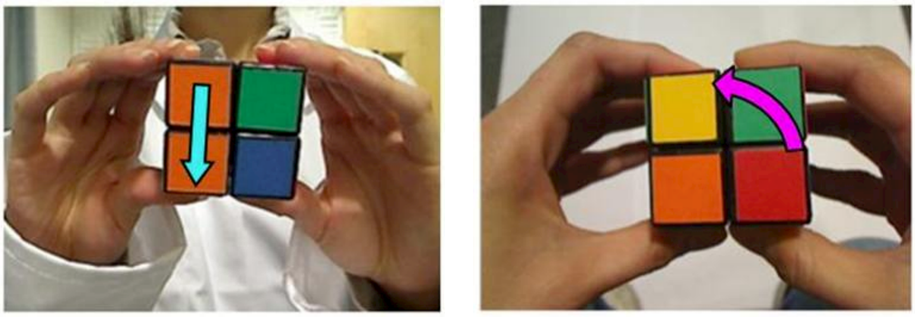
To date no research comparing user performance of object manipulation between see-through window and magic mirror views appears to have been done. The most relevant is the study conducted by Jeon et al. (2006), which compared users' performance in matching a virtual teapot registered on a 2D marker to a target virtual teapot, under three different camera viewpoints of a monitor-based display setup (Figure 4.3). All three viewpoints provide tilted top views of the workspace, with the first over the user's head, the second next to the user at eye level, and the third in front of the user.

Results showed that users spent the longest time to complete the task in the third viewpoint condition. The authors argued that the poorer performance in this condition is due to significant viewpoint mismatches between the user and the camera. Although this experiment is informative for general usability of monitor-based displays, its usefulness is limited to answer the research question of performance difference between see-through window and magic mirror views for two reasons. First, although the first two conditions provide viewpoints close to a first person view, they are different from the see-through window metaphor that follows the eye-screen-workspace setup. Second, the tilted top view of the third condition differs greatly from a mirror view, which includes a mirrored image of the front view of the user and workspace. Therefore the perceptual adaptation involved in the third condition is not directly comparable to the one in a mirror view.

Figure 4.4: The AR book setup of Dünser and Hornecker (2007)'s study.

The viewpoint mismatch was also reported in the study of the ALIVE system. The authors pointed out that users were unlikely to feel disoriented with the ALIVE system compared to virtual reality systems with an egocentric view. The camera capturing live video, however, was fixed on top of a large screen that was significantly above eye level, and so produced a trapezoidal distortion which might require additional cognitive processing (Maes et al., 1995).

Compared to adults, children have reduced eye-hand coordination skills due to their developmental stage (Strommen et al., 1996). In exploration of usability issues of children interacting with AR applications, Dünser and Hornecker (2007) observed children aged six to seven interacting with an AR book. The AR book consisted of a desktop monitor, a web camera pointed at the table from the top of the monitor, and a paper-based story-book with 2D markers attached (Figure 4.4). Children interact with virtual contents registered to the AR book through 2D markers. During this interaction, intermittent spatial confusion was observed due to the mirror-effect that reversed the front and back of the AR book. The authors reported that this confusion caused children to momentarily shift attention from the screen to the physical workspace, but did not affect the overall user experience. In both this and Jeon et al.'s study, users manipulated 2D markers, which are less common in real life and more constrained than manipulating objects with three-dimensional qualities.



(a) Magic mirror view (b) See-through window view

Figure 4.5: The user's view of instructions augmented on the Rubik's cube.

In summary, I believe that the knowledge gap of using an AR magic mirror to support bimanual manipulation of physical objects is due to the conceptual bias regarding mirror reversal. I intend to examine the extent to which people are confused when manipulating physical objects in a mirrored view. In the following sections, I report a usability study that compares users' visuomotor performance when following virtual rotation cues in both a mirror and see-through view.

4.3 Method

In this study, I conducted an experiment to compare the speed and accuracy of a user manipulating a simplified (2x2x2) Rubik's cube by following augmented rotation instructions presented under two display conditions: magic mirror and see-through window. Figure 4.5 shows what the participant sees from the display under each condition.

The rotation task is chosen because it requires demanding visuomotor skills. Mental rotation is a well-established research method that has been applied in numerous visuospatial-related research projects (Zacks, 2008). In the original mental rotation experiment, subjects had to decide whether two objects with different orientation are identical or mirrored versions of each other, by mentally rotating the three-dimensional object (Shepard and Metzler, 1971). The rotation task in mental rotation experiments is a representative object manipulation exercise that requires high-level visuospatial skills (Goodale and Westwood, 2004). Therefore the subject's ability to rotate a three-dimensional object under a mirror view should be a representative task of overall visuomotor performance under the mirror view.

Based on the above considerations, I decided to adopt rotation as the object manipulation task in the experiment to evaluate performance differences between the two display metaphors. A Rubik's cube was chosen as the physical object in the rotation task because (1) it is a familiar object that requires a user to use both hands to manipulate; (2) it supports comprehensive rotation tasks involving whole- and part-object rotation around all three axes.

I chose two measurements to evaluate the efficiency and effectiveness of participants manipulating objects under the two different AR display metaphors: speed and error rate. Consequently there are two null and alternative hypotheses in our experiment:

- $\mathbf{H}_{0A}$: There is no significant difference between the mirror and see-through views in the speed of following rotation instructions.

  $\mathbf{H}_{1A}$: There is a significant difference between the mirror and see-through views in the speed of following rotation instructions.

- $\mathbf{H}_{0B}$: There is no significant difference between the mirror and see-through views in the number of errors while following rotation instructions.

  $\mathbf{H}_{1B}$: There is a significant difference between the mirror and see-through views in the number of errors while following rotation instructions.

4.3.1 System Implementation

I developed an AR system to superimpose visual guidance on specific parts of the Rubik's cube for rotation (as shown in Figure 4.5), detect the completion of expected rotation, and superimpose the next rotation guidance. The recognition process is implemented with the computer vision open source library OpenCV 2.0 (OpenCV.org, 2009). The main procedure of the system is described below:

1. The system first generated a sequence of random rotation actions with equal occurrence frequency. The sequence was then fed to the Rubik's cube detection program.

2. The program detected the colour pattern of the Rubik's cube face facing the camera (I call it "front face" in this chapter although note that this

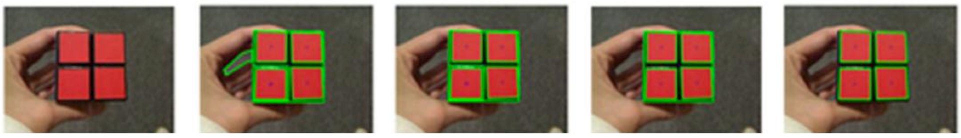


Figure 4.6: Rubik's cube face detection. The five recognition steps from left to right are: capture original image; contour detection; remove concaves, large and non-square contours; remove redundant squares; remove the outline square.

visible face is oriented either towards or away from the user, depending on the viewing condition). Once the initial face pattern was detected from the camera image, the system superimposed the first rotation instruction over the screen image of the Rubik's cube.

3. The program calculated the next expected Rubik's cube face pattern according to the current rotation cue and waited for it to appear. This process repeated until the end of the action sequence.

In order to ensure the robustness of the Rubik's cube detection performance, I decided to only detect the side of the cube facing the camera rather than tracking the whole cube in 3D using model-based rigid object tracking (see Section 2.1.2). This is mainly because a Rubik's cube is not completely rigid due to its rotatable feature. For each RGB colour channel, the system applied a sequence of filters to detect the four squares of the front face of the cube (Figure 4.6). Each time the camera captured a new image, it first detected all contours, and then went through three filters to remove non-square contours (e.g. concaves, contours with more than four vertices), large or redundant square contours and the outline contour of the front face of the cube.

The IHS colour space (Sangwine and Horne, 1998) was used for the colour recognition of individual squares of the detected face. IHS is a three-dimensional colour space calibrated for human perception. It separates intensity from hue and saturation which enables colour recognition under different lighting conditions. For each of the Rubik's cube colours, I collected hue and saturation information of 256 pixels under five lighting conditions (see Figure 4.7) and trained them into a k-nearest neighbour classifier (Cover and Hart, 1967; Cunningham and Delany, 2007).

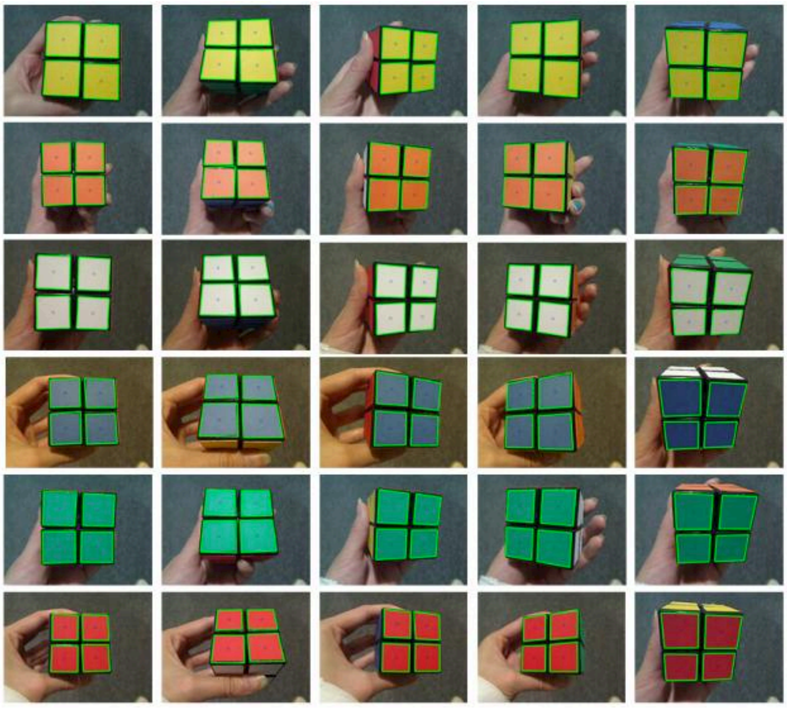
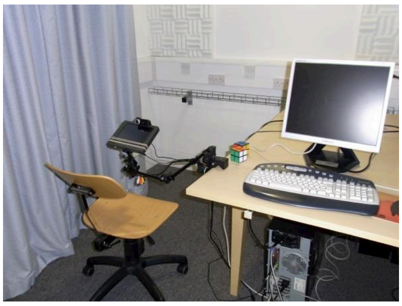


Figure 4.7: Training data for the k-nearest neighbour classifier in five lighting conditions.

Once the system detected a face, the centre pixel of each square was retrieved and sent to the classifier. In our system, k was set to 20, which means the system assigned the colour of the highest frequency among the top 20 closest neighbours in Euclidean distance to the input pixel. When the colours of all four squares matched the expected front face status, the system acknowledged the completion of the expected rotation action and rendered the visual cue for the next action.

4.3.2 Participants

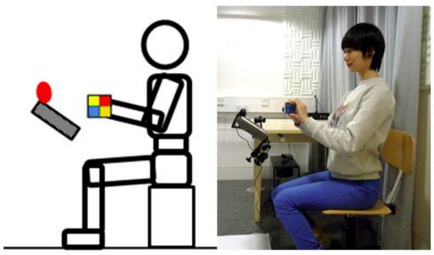
I recruited 15 participants, 8 male and 7 female, aged between 15 and 55 years old (seven participants aged 15-25, seven aged 26-35 and one aged 46-55). Three participants had no experience with solving a Rubik's Cube while the rest claimed they had beginner skills. There were 7 participants who were graduate students and 8 participants who were local residents. They signed up for the experiment via an online advertisement. Ethical permission was approved and all participants



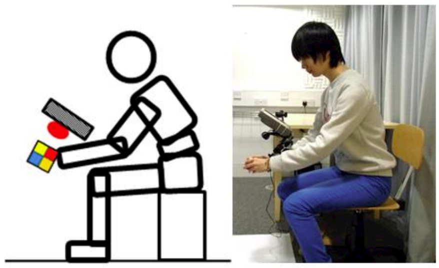
(a) Equipment setup in the usability experiment laboratory

(b) VGA monitor, Logitech Webcam, and Rubik's cubes

Figure 4.8: Experiment Apparatus.



(a) Mirror view setup



(b) See-through view setup

Figure 4.9: Experiment setup in each viewing condition.

completed a consent form (see Appendix A.1) and were compensated with a ten-pound voucher.

4.3.3 Apparatus

The system was composed of a desktop PC (Intel Pentium CPU 3.20GHz, 6.00 GB RAM), an 8-inch VGA monitor (LILLINPUT 809GL-80NP/C/T with 4:3 aspect ratio) and a Logitech Webcam Pro 9000 (30 frames per second video) (Figure 4.8). According to the different viewing conditions, there were two versions of the hardware setup (Figure 4.9).

The height of the chair on which the participant sat was 47cm. The distance between the bottom of the screen and the ground was 80cm. The screen was an-

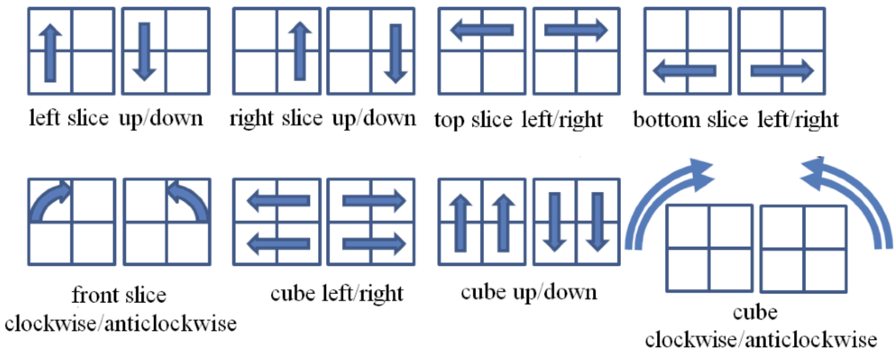


Figure 4.10: Sixteen different rotation cues.

gled at 25 degrees above the horizontal. This was consistent in both conditions, while the participant could adjust the distance between the chair and the display to sit in a comfortable position. The setup for the mirror view is shown in Figure 4.9(a). A webcam was mounted on top of the monitor facing the participant. During the experiment, the participant held the Rubik's Cube in front of him or her with the front face of the cube facing directly at the webcam. The screen displayed an image similar to the cube being held in front of a mirror. The setup for the see-through view is shown in Figure 4.9(b). A webcam was fixed at the back of the monitor in a parallel manner. The participant held the Rubik's Cube behind the monitor and saw the cube and his or her hands through the monitor as if they were being viewed through a window.

4.3.4 Experiment Design

A within-subjects experiment was conducted. There were two sessions, one for each viewing condition (see-through window or magic mirror) and counterbalanced across participants. In each session the participant completed three tasks. Each task required the participant to manipulate the Rubik's Cube by following a sequence of visual cues as quickly and as accurately as possible. There were sixteen possible rotation cues (Figure 4.10). The sequence of required rotations was generated in a pseudo-random way to include all sixteen cues.

I measured response times individually for each rotation. This was calculated by recording the time interval between the visual presentation of a cue, and the point at which the machine vision system recognized that the rotation had been completed and presented the next cue. In addition, I counted user rotation errors by manually coding the screen recording. There are two types of error in the experiment. Errors of the first type are those made by the participant without realizing it was wrong and only corrected after being pointed out by the experimenter; the second type are those that the participant realized immediately after he or she made the wrong rotation and corrected it by her/himself. Participants were informed that they need to keep their fingers away from the front face of the cube after each rotation, in order to avoid delay of Rubik's cube recognition.

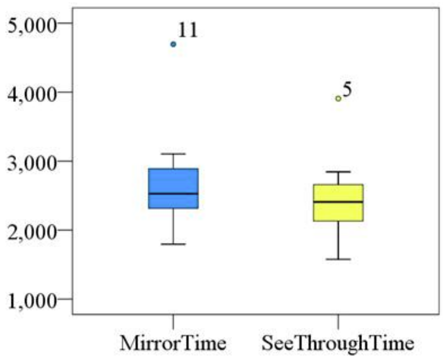
Furthermore, I collected feedback from participants by asking them to fill in a questionnaire after the experiment (see Appendix A.2). It required the participant to rate the system with a five-level Likert item in three different aspects under each viewing condition: ease of following the instructions, confidence and comfort. It also asked the participants which version of the system was more natural to use. The questionnaire coded the viewing conditions as "the first version" and "the second version", so that it would not impose the mirror or see-through metaphor on the participant. A short interview was conducted after the questionnaire in order to understand the reason behind their answers.

4.3.5 Procedure

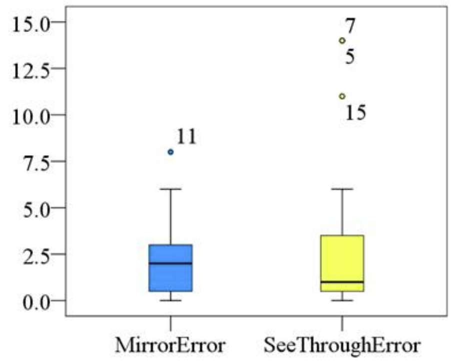
The experiment contained seven steps: (1) the experimenter demonstrated how to use the system with the first view; (2) a practice task was given to the participant. He or she could practice multiple times until he or she felt confident to start the formal tasks; (3) the participant finished three formal tasks in a row; (4) the participant took a 15-minute break to avoid fatigue; (5) the participant repeated steps (1) - (3) with the second view; (6) the participant completed a questionnaire; (7) the experimenter interviewed the participant to discuss the questionnaire answers.

4.4 Results

This section presents the participants' performance in speed and error rate, breakdown of results according to rotation types, and subjective feedback.



(a) Time per rotation



(b) Number of errors under the two viewing conditions

Figure 4.11: Results of speed and error of users' performance under the two viewing conditions.

4.4.1 Speed

The speed per rotation is normally distributed among participants. The boxplot chart of the average time per rotation (millisecond) in both displays is shown in Figure 4.11(a). The average time per rotation of the magic mirror view is longer than the see-through window view by 215ms. This difference, however, is not statistically significant according to the paired t-test: $t(14) = 1.4, p = 0.18 > 0.05$.

4.4.2 Error

A nonparametric paired Wilcoxon signed-rank test was conducted since neither of the samples was normally distributed. There is no significant difference between the two views in the number of errors: $Z = -1.1, p = 0.92 > 0.05$. The boxplot shown in Figure 4.11(b) reveals that the median value of error numbers was slightly bigger in the magic mirror view than the see-through window view.

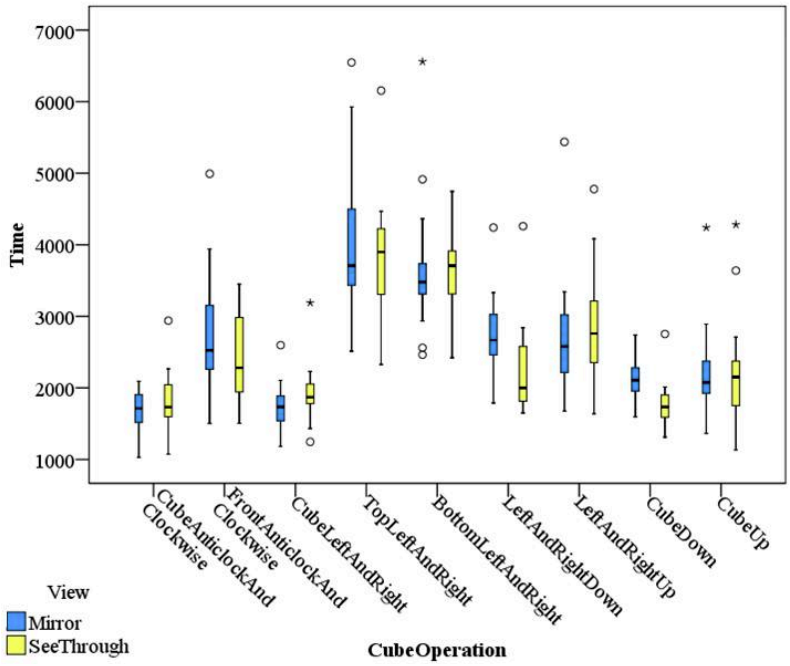


Figure 4.12: Comparison of rotation speed with different action types.

4.4.3 Results Breakdown

Speed vs. Rotation Types

According to the experiment design, sixteen action types were evenly presented across each task. I collected the median value of time per rotation (in milliseconds) for each action type among the fifteen participants. The initial results showed no noticeable left-right asymmetry, therefore I aggregated the results of all left-right and clockwise-anticlockwise pairs. The boxplot of the average time per rotation of each type is shown in Figure 4.12.

We can see that the average time per rotation of most action types between the two views are paired, except rotations involving downward movement. To further investigate the performance with different action types, I conducted a paired t-test and the results showed there was no significant speed difference in actions involving left/right direction between the mirror and see-through views:

$t_{CubeLeftAndRight}(14) = -1.39, p = 0.19 > 0.05$

$t_{TopLeftAndRight}(14) = 1.15, p = 0.27 > 0.05$

$t_{BottomLeftAndRight}(14) = 0.46, p = 0.66 > 0.05$

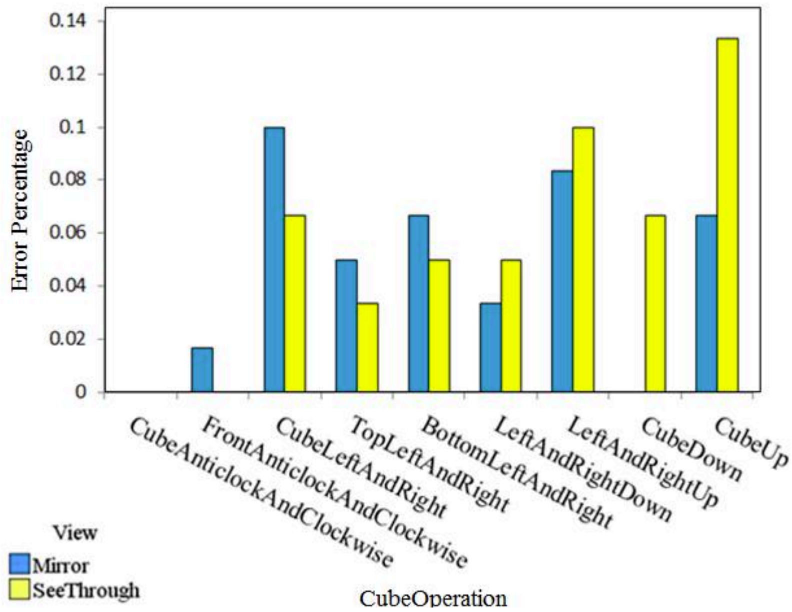


Figure 4.13: Comparison of percentage of errors with different action types.

Nevertheless, I did find a significant lower speed of downward rotation in the magic mirror view.

$t_{CubeDown}(14) = 3.84, p = 0.002 < 0.01^{**}$

Error vs. Rotation Types

I calculated the average percentage of errors for each type of rotation since there is a noticeable individual difference in error counts. From Figure 4.13 we can see that participants on average tended to make slightly more errors in the mirror view for rotations involving left and right directions. On the other hand, they made more errors in the see-through view for rotations involving up and down directions, although none of these differences is shown to be significant using the nonparametric Wilcoxon signed-ranks test.

4.4.4 Participants' Feedback

It is intriguing that 13 out of 15 participants preferred the first view they experienced according to the questionnaire. One of the other two participants had no preference, and one explained in the follow-up interview that he had previous

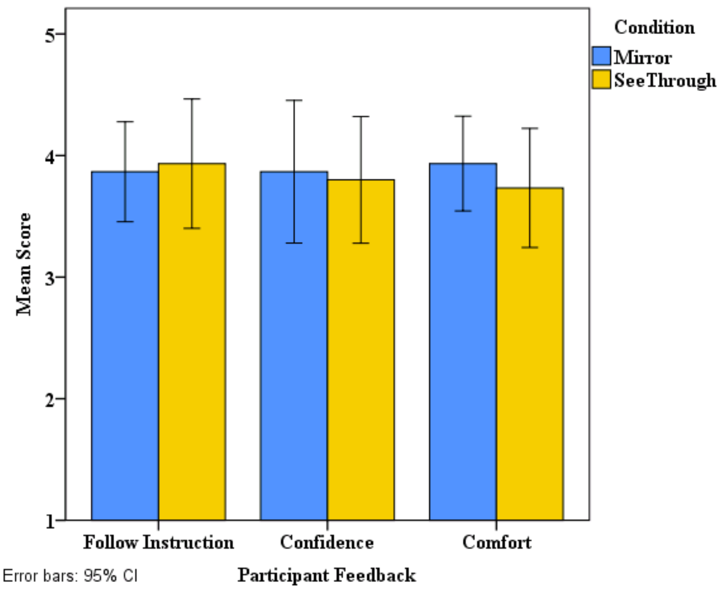


Figure 4.14: Participant feedback on ease of following instructions, confidence and comfort of the two viewing conditions.

experience with commercial AR games using a see-through window metaphor. In addition, I asked the participants to rate the degree of ease of following instructions, confidence and comfort of both viewing conditions (Figure 4.14) and results show that there is no significant difference in any of the above user experiences. These results indicate that it is easy for the majority of users to adapt to the first viewing condition of an AR system to which they are introduced regardless of whether it is a magic mirror or see-through window view.

4.5 Discussion

In this section, I discuss the major findings based on the experiment results, the related implications for object manipulation in a magic mirror view, and study limitations.

4.5.1 Major Findings

Neither null hypothesis H_{0A} or H_{0B} is rejected because the experiment results show no significant difference in speed and error in the Rubik's cube rotation task between the see-through window and magic mirror views. To state our findings conservatively, although there may be a mirror-effect that would be detectable with a larger experimental sample, our results indicate that the size of such an effect, if present, is only small. These findings suggest that participants developed comparable abilities of object manipulation involving complex visuomotor skills in both views after minimal learning periods. This result complies with perceptual adaptation theory that the human brain can adapt to altered visual fields within a certain time of exposure. This result is further supported by participants' feedback on comparable user experiences in ease of following instructions, confidence, and comfort. In addition, the participant questionnaire showed that the majority of participants preferred the first viewing condition during the experiment, regardless of whether it was see-through window or magic mirror. This obvious preference implies that the two visuomotor coordination systems are comparably easy for participants to adapt to when introduced in the first place. It also suggests that extra cognitive effort is required to switch one's visuomotor mapping from the first to the second view, an explanation supported by participants' feedback during the interview.

Overall the major findings above indicate that users perform bimanual object manipulation involving complex visuomotor skills with comparable efficiency and effectiveness in the magic mirror view compared to the see-through window view. This is an important implication for design of an AR magic mirror to support symbolic play.

The major difference between the AR magic mirror setup in this study and monitor-based AR displays used in Jeon et al. (2006) and Dünser and Hornecker (2007) studies (see Section 4.2.3) is that the former simulates a first person view through a vertical mirror, which resembles users' existing experience with mirror perception; while the latter provides a significantly tilted mirror view, which causes extra and unfamiliar visuomotor adaptation. Since both magic mirrors and see-through windows are familiar experiences in people's lives, the findings support the importance of applying metaphors to accelerate users' learning processes of novel user interfaces as discussed in Section 2.3.2.

4.5.2 Implication of Mirror Reversal

As previous psychology experiments indicate, people believe reflections move the same way when they see movements approximately parallel to the mirror (Savardi et al., 2010). If we consider left/right rotation a special case of parallel movements around the pivot, this may explain why there is no significant difference of speed and error among left/right rotations between the two viewing conditions. The implication of these findings is that when designing object manipulation scenarios under a magic mirror view, one should avoid encouraging movements that are non-parallel to the screen to mitigate orientation confusion.

In addition, I found that the speed of downward rotation is significantly slower in the mirror view. I observed that participants tended to over rotate the cube downwards and follow up with a slight upward adjustment in the mirror view. This might contribute to the slower speed for downward rotation. One potential cause could be that downward rotation requires performing an outward rotation of hand from the wrist, which is less commonly practiced in daily life than inward rotation (e.g. drinking water from a cup). Such human motor skill issues need to be carefully considered when designing related applications in a mirror view. On the other hand, although the difference was not statistically significant, Figure 4.13 shows that participants tended to make more errors in whole cube up and down rotations in the see-through window view. During interviews, some participants reported that they obtain a better sense of vertical orientation in the magic mirror view because they can see their own body. This is because the asymmetry of body image provides strong orientation cues for the up/down direction and the upright body image also reassures a sense of gravity, which is a critical direction reference for vertical orientation (Dyde et al., 2009). In short, the finding suggests that the inclusion of body image in a magic mirror view is beneficial to provide a strong sense of upright orientation for object manipulation.

4.5.3 Limitation

This study is a preparatory investigation for object manipulation with an AR magic mirror. There are two main limitations of this study that require caution for readers to interpret the findings. First, I chose the three-dimensional rotation as a demanding bimanual object manipulation task to examine subjects' visuomotor abilities in a magic mirror view. There are yet other types of object manipulations such as translation that are commonly involved in daily activities. A full exploration including these types of manipulation tasks will lead to a comprehensive understanding of mirror-effects in object manipulation with the AR magic mirror. Second, the experiment only included a small number of participants and it did not involve child users. The goal of this study was to obtain a preliminary understanding of general user performance with the AR magic mirror, therefore the experiment is rather compact and saved the participation of child users for formal studies conducted later, who are much more difficult to recruit than general adult users.

4.6 Conclusions

I made a novel comparison of user performance in a visuomotor task between AR displays using the magic mirror and see-through window metaphors. The results suggest that users' overall performance under the mirror view is comparable to the see-through view, and that the AR magic mirror is a reasonable alternative for AR applications involving moderately complex object manipulation.

I found the majority of participants prefer the first view to which they were introduced. This suggests that the designer of AR applications can choose the most appropriate viewing condition based on an actual user scenario without being constrained by the current research emphasis on see-through window. Although object manipulations in real life are more complex than those constrained to the three-dimension Cartesian axes and usually associated with nonlinear movements, results in this paper still relate to a fundamental aspect of users' performance which is of value in suggesting the design of future AR applications.

As a summary, the rotation task in our experiment addressed a critical issue regarding complex object manipulation in three-dimensions, which would appear less likely to be intuitive under mirror reversal. Our focus on bimanual manipulation is directly related to symbolic play activities. While HMD remains expensive and mobile handhelds hinder bimanual activities, the AR magic mirror appears a bimanual-friendly and economical alternative. The findings are informative for the design of AR systems with the magic mirror metaphor to enhance symbolic play in Chapters 5 and 6. Further usability issues are also investigated in these chapters relating to object manipulation in the play context with child users.

Chapter 5

An AR Interface to Promote Solitary Symbolic Play for Children with ASC

5.1 Introduction

ASC is a neurodevelopmental condition characterized with impaired social communication and interaction, and restricted and repetitive behaviours, interests or activities (American Psychiatric Association, 2013). In particular, children with ASC often have difficulties in sharing imaginative play. In Chapters 2 and 3, I presented a review of the theoretical research of symbolic play deficits among children with ASC due to cognitive and executive dysfunctions, and elaborated a progressive AR design approach to enhance symbolic play. Preliminary usability results from Chapter 4 showed that the AR magic mirror is promising to support bimanual manipulation of physical objects for general users, which prompts further usability investigation with child users. Based on the above findings, in this chapter I describe the development and evaluation of an AR system with the magic mirror display metaphor to explore the potential of AR in promoting solitary symbolic play for young children with ASC. This study tackles the three research questions established in Chapter 2:

- What are key design considerations of AR systems that promote symbolic play for young children with and without ASC?

- How usable is the magic mirror display metaphor in supporting object manipulation in symbolic play?

- What are key considerations to rigorously evaluate the effectiveness of AR systems in promoting symbolic play for young children with and without ASC?

The first research question was raised based on the theoretical relationship between AR and symbolic play, and the advantages of AR to overcome limitations of conventional intervention (see Chapters 2 and 3). Solitary symbolic play is the early form of symbolic play that appears in the latter half of the second year among typically developing children (Piaget, 1962). It involves the fundamental cognitive mechanism of symbolic transformation and lays the cornerstone for the later social symbolic play, which involves more sophisticated social and communication skills. Therefore, exploring the design space of AR interfaces to promote solitary symbolic for children with ASC is a critical stride towards the understanding of the potential effectiveness of the proposed AR approach in enhancing symbolic play.

The second research question was developed based on the analysis that the AR magic mirror is suitable to support key features of symbolic play, but there is a lack of related usability research on bimanual manipulation of physical objects under the magic mirror view (see Section 2.3.2). The results presented in Chapter 4 show that adult users can carry out object manipulation with comparable efficiency and effectiveness in the magic mirror view compared to the see-through window view. Based on these preliminary findings and associated design guidance in response to mirror reversal, I apply the magic mirror display metaphor to the AR system for solitary symbolic play enhancement in this study. By observing how usable the AR system is for young children with ASC, I extend the usability research of using an AR magic mirror to support object manipulation to child users.

The third research question was proposed due to the lack of rigorous evaluation methods for AR applications involving complex cognitive processes, and the special challenges for experiment design brought up by limited abilities of young children with and without ASC (see Section 2.3.3). In this chapter, I describe a rigorous evaluation approach by exploiting experiment methods described in psychology literature of symbolic play and adopting considerations of general neurodevelopmental deficits of autistic children.

The design and evaluation of the AR system in this study largely referred to psychology literature in symbolic play and autism. In the design phase, I probed the design space in two main aspects: symbolic transformation and play theme. First, I considered the progressive AR design approach elaborated in Chapter 3 as the underlying design structure to visualize symbolic transformation. Second, I used psychology literature as the reference to design play contents appropriate for children with ASC, who show a restricted repertoire of interests (Gillberg et al., 2001; Rapin, 1991). In the evaluation phase, I designed experiment methods for the AR system by referring to psychology literature in three aspects: autism specific symptoms, level of symbolic play prompt, and measures for symbolic play. First, children with ASC experience impairments in social interaction and communications to various extents (Lord et al., 2000; Schopler et al., 1980). These conditions have to be carefully addressed in order to avoid early withdrawal or reduced performance from intrinsic factors unrelated to the AR system. Second, adult prompts for symbolic play range from no prompt (spontaneous) to highly instructed (e.g. modelled behaviour) in psychology experiments. Defining the level of prompt that the AR system provides is essential to design appropriate conditions in the controlled experiment. Third, the identification and evaluation of symbolic play behaviour from a sequence of dynamic play episodes can be challenging due to the diverse forms of pretense and level of ambiguity (Jarrold, 2003). Therefore measures used in previous psychology experiments are an informative reference.

Based on the review of the above literature, I designed and evaluated an AR system that explored the potential of AR technologies in promoting solitary symbolic play for young children with ASC, by visually conceptualizing the cognitive mechanism of symbolic thought within an open-ended play environment. Results from an empirical study involving autistic children aged 4 to 7 confirmed that the AR system can help participants carry out symbolic play more frequently, maintain longer symbolic play duration, and regulate play ideas more consistent to suggested themes. Participants were highly engaged with the AR system and preferred the AR system to non computer assisted play. In addition, I found a gradual level of effectiveness of symbolic play enhancement according to individuals' autistic condition, based on the analysis of individual differences in terms of minute-by-minute play behaviour, and the symbolic use of non-augmented objects. Insights of usability discoveries were then discussed in Section 5.8.6 to inform the design of future AR systems with the magic mirror metaphor intended for children with ASC.

The remainder of the chapter is structured as follows. In Section 5.2, I review psychology literature of considerations of symptoms among children with ASC and symbolic play experiment methods to inform the design and evaluation of the AR system. In Section 5.3, I present the detailed system design based on the progressive AR design approach proposed in Chapter 3. In Section 5.4, I describe the system implementation. In Section 5.5, I discuss expert feedback, the pilot study with young children with and without ASC, and corresponding improvements for the experiment design. In Section 5.6, I describe the design of a controlled experiment to evaluate the effectiveness of the AR system for symbolic play enhancement. In Section 5.7, I report the experiment results and in Section 5.8, I discuss the major findings and study limitations. In Section 5.9, I summarize findings in response to the three research questions respectively.

5.2 Related Work

In this section, I first investigate symptoms among children with ASC including restricted interests and activities, impaired communication skills, and individual differences in impairment. This investigation informs potential play contents for the AR system, and important considerations to accommodate autistic children's special needs during the controlled experiment. I then investigate degrees of prompts used in empirical experiments of symbolic play with autism, including spontaneous, elicited and instructed. Consequently, I identify the prompts of the AR system as lying between elicited and instructed prompts. Last, I investigate the measures of symbolic play used in previous research including measurement methods and coding schemes to guide the experiment design of this study.

5.2.1 Autism Related Symptoms

Children with ASC exhibit a wide range of difficulties in social interaction, communication and restricted and repetitive behaviours (see Section 2.2.2). These deficits not only affect children's experience when interacting with unfamiliar computer systems, but also make it particularly difficult for them to participate in unfamiliar environments such as controlled experiments. In this section, I identify potential impacts and considerations of these deficits in the design and evaluation of the AR system in this study.

Restricted Interests and Activities

People with ASC often show restricted interests on certain topics, such as systems with structures and rules (Baron-Cohen and Wheelwright, 1999; Richler et al., 2010). Especially, clinical reports show that a number of children with ASC have a strong preference for vehicle toys (Baron-Cohen, 2002). Applying a child's interest is considered an effective approach to increase motivation of appropriate play behaviour (Baker et al., 1998). For example, "The Transporters" is an animation story series made up of animated vehicles with human faces. It makes use of autistic children's obsessive interests in vehicles, spinning objects and computers to enhance their emotion comprehension (Baron-Cohen et al., 2007; Golan et al., 2010). Similarly, "train" is suggested as a special topic to teach autistic children various skills such as reading, math and symbolic play (Grandin, 2002; Porter, 2012). Other vehicles such as cars and airplanes have been commonly used as play materials in experiments on symbolic play deficits and interventions with autism (Blanc et al., 2005; Kasari et al., 2006; Lewis and Boucher, 1995; Libby et al., 1997; Lifter et al., 2005; MacDonald et al., 2009; Toth et al., 2006; Ungerer et al., 1981).

The high predictability of computers is a favourable feature for children with ASC (Grynszpan et al., 2013). Obsessive interest with machinery, however, may be a distraction while interacting with novel computer systems. Autistic children may become too curious about the way the system works to fully engage in the designed learning scenarios. For example, when interacting with a tangible system to practice music composition by arranging 2D markers on a board, a group of autistic children aged 11- 15 were reported to look away from the workspace and inquisitively explore the camera above the workspace and the computer screen on the other side of the table (Farr et al., 2010). Informed by previous studies, I consider the obsession with computer systems as an unwanted external stimulus and thus apply several methods to avoid such distraction in order to guide children's focus to meaningful interactions with the AR system in this study.

Rigid routines and resistance to change is especially adverse for controlled experiments, which takes children away from their familiar routine and requires them to cooperate with experimenters previously unknown to them. This can cause excessive fear or nervousness for some children with ASC, who are extremely difficult to calm or comfort in unfamiliar situations compared to the reaction of a typically developing children of the same age (Schopler et al., 1980). Visual supports such as a schedule or image sequence are common methods used by caregivers and teachers to regulate daily repertoires of autistic children by replacing spoken and written instructions with alternative visual cues (Mirenda, 2001). They have also been used in HCI studies to reduce unpredictability of experiment activities (Frauenberger et al., 2012), which is recognised as an important factor to help adapt to changes (Howlin, 1998). In this study I refer to the above considerations in the experiment design to eliminate impacts of the unfamiliar scenarios on children with ASC, so that participants' play behaviours can reliably reflect the effectiveness of the proposed AR system.

Impaired Communication

Children diagnosed with ASC show various levels of impairment in communication, which include delayed language, impairment in initiating and sustaining conversation, and stereotypical and repetitive use of language (American Psychiatric Association, 2013). The correlation between symbolic play and language was found in several studies on symbolic play development (Blanc et al., 2005; McCune-Nicolich, 1981; Mundy et al., 1987; Sigman and Ungerer, 1984; Toth et al., 2006). As a result, language ability in terms of receptive and expressive verbal scale has been commonly used as a matching criterion for symbolic play comparison between children with and without ASC (Baron-Cohen, 1987; Gould, 1986; Hobson et al., 2009; Lewis and Boucher, 1988, 1995; Libby et al., 1998; Wetherby and Prutting, 1984). Some common language measurement systems include the British Picture Vocabulary Scale (BPVS) (Dunn and Dunn, 1982) and the Reynell Developmental Language Scale (Reynell and Huntley, 1987).

In addition, impaired communication ability can affect the collection of autistic children's experience with computer systems. Since mental models of child users are distinct from adult users, it is important to use questionnaires or interviews to gather children's opinions on system usefulness, fun, and requirements for future design (Druin et al., 1998; Read et al., 2001). Considering children's limited ability to understand and report in response to questions, Read and MacFarlane (2006) proposed the Fun Toolkit survey method for child users. The Fun Toolkit has a special emphasis on using visual props to help children understand and articulate ideas, which makes it essentially a visual support tool for user experience investigation for children. Similarly, Self-Assessment Manikin (SAM) is another well-known non-verbal pictorial assessment tool that measures a wider range of peoples affective reaction to external stimuli including pleasure, arousal and dominance (Bradley and Lang, 1994). Delayed communication development of children with ASC makes such investigation even more difficult. As a result, most empirical studies of computer technologies designed for autistic children rely on user observation to indirectly explore user experience such as enjoyment and attentiveness (Alcorn et al., 2011; Barakova et al., 2007; Farr et al., 2010; Hirano et al., 2010; Richard et al., 2007; Stanton et al., 2008).

Gathering feedback from children with ASC has recently drawn researchers' attention in the field of participatory design with children, which actively involves children's inputs in the design process of computer interfaces (Druin et al., 1998). Researchers in this domain develop several survey methods based on visual support principles for child-computer interaction to facilitate autistic children to provide meaningful design contributions. For example, Frauenberger et al. (2012) developed an annotation tool as part of the ECHOES project to allow autistic children aged 8-13 to comment on a virtual character environment using stamps of different faces. Millen et al. (2011) proposed a visual schedule to structure children with ASC aged 13-14 through six different design activities for a computer game. Benton et al. (2012) developed a visual schedule method called IDEAS, which guides children with ASC aged 12-13 to collaborate in a computer game design activity. These survey methods implementing visual support principles are informative to the experiment design in this study.

Additional Impairments and Individual Difference

In addition to the core deficits discussed above, children with ASC are often found to experience impaired motor abilities (Green et al., 2009; Ming et al., 2007; Provost et al., 2007). As discussed in Chapter 4, AR magic mirrors require certain visuomotor and perception adaptation skills. Therefore, it is important to examine usability issues of autistic children using the AR magic mirror proposed in this chapter. Moreover, unusual sensory behaviours commonly found with autistic children may also affect participants' experiences during a controlled experiment (Leekam et al., 2007; Lord et al., 2000; Rogers and Ozonoff, 2005). Sensory affects pertain to visual, auditory, touch, and smell. Knowing participants' special sensory behaviours in advance is critical to avoid disturbance from the experiment environment.

The high diversity of the spectrum of symptoms under ASC presents considerable challenges to diagnosis and treatment. Individual differences among autistic children are considered important to inform the detailed intervention effects on children with varied levels of impairment under the autism spectrum. (Howlin et al., 2009; Trembath and Vivanti, 2014; Wieder and Greenspan, 2003). It is suggested that individual differences can help predict intervention outcomes and match children to certain treatments that are more suitable to their condition (Trembath and Vivanti, 2014). Identifying individual differences is especially feasible for studies with small sample sizes, in order to predict invention outcomes on a larger population with different subgroups of individuals (Howlin et al., 2009). As the user group of children with ASC is relatively scarce for HCI research, the sample size of most studies is very small (Lazar et al., 2010). Therefore I am motivated to address individual differences of symbolic play enhancement using the proposed AR system in this study.

5.2.2 Level of Symbolic Play Prompts

As reviewed in Section 2.2, physical and verbal prompts are often given in psychology experiments of symbolic play deficits with autism. Three levels of prompt are commonly adopted in these experiments: spontaneous, elicited and instructed (Charman and Baron-Cohen, 1997; Hobson et al., 2009; Jarrold et al., 1996; Lewis and Boucher, 1995; Libby et al., 1997; Riguet et al., 1982; Rutherford et al., 2007; Sigman and Ungerer, 1984; Ungerer et al., 1981). Spontaneous play refers to free play behaviours in unstructured settings without adults' prompts. Meanwhile, both elicited and instructed play refer to play behaviours in a structured setting with an increasing level of adult prompt. During elicited play, the experimenter gives the child non-specific verbal prompts to encourage the use of play materials, such as "show me what you can do with these" (Jarrold et al., 1996), or "show me what the car can do" (Lewis and Boucher, 1995). During instructed play, the experimenter gives specific instructions to encourage children to carry out or imitate certain play acts, such as "show me how the girl can be scared of a dog" (Jarrold et al., 1996), or modelled play acts like "feed the monkey with a spoon (using a Popsicle stick)" (Riguet et al., 1982).

Symbolic play prompted by the AR system in this chapter resides between elicited and instructed symbolic play because the symbolic transformation suggested by the AR system provides more cognitive scaffolding than the elicited condition, while its open-ended play mode provides less scaffolding for conceiving and acting out play ideas than the instructed condition. The advantage of the AR approach compared to instructed play is that it can visually illustrate the mental processes of symbolic transformation, while giving children the freedom to think of and carry out related play ideas in an open-ended manner. In this thesis, I call symbolic play prompted by the AR system "AR elicited symbolic play" to differentiate it from conventional elicited symbolic play.

5.2.3 Measures for Symbolic Play

It is a great challenge to identify and measure symbolic play behaviours due to the complex and diverse mental processes involved. In this section I investigate the two main aspects of symbolic play evaluation in previous psychology experiments: coding scheme and measurement. Research in these two aspects shows how to identify and measure symbolic play respectively, which are core considerations of experiment design in this chapter.

First, the coding schemes commonly used in autism research include symbolic play, functional play, relational play, simple/sensorimotor play, and no play (Baron-Cohen, 1987; Charman and Baron-Cohen, 1997; Jarrold et al., 1996; Lewis and Boucher, 1995; Libby et al., 1998; Sigman and Ungerer, 1984; Toth et al., 2006; Ungerer et al., 1981). Although there is a slight variation between studies, the definition of each play form essentially complies with developmental psychology literature. In particular, most studies refer to symbolic play as play behaviours involving any of the three forms of pretense defined by Leslie (1987): object substitution, attribution of pretend properties and imagination of absent objects.

Second, existing measures are informative for designing measurements for this study. Measurements applied in research on immediate symbolic play enhancement with autism can be divided into quantitative and qualitative. Quantitative measurements examine the amount of symbolic play via frequency (Lewis and Boucher, 1995; Mundy et al., 1987; Riguet et al., 1982; Sigman and Ungerer, 1984; Ungerer et al., 1981), duration (Jarrold et al., 1996; Lieber and Beckman, 1991; Sigman and Ungerer, 1984; Ungerer et al., 1981), and number of correct responses to instructions (Charman and Baron-Cohen, 1997; Jarrold et al., 1996; Lewis and Boucher, 1995; Libby et al., 1997; Rutherford et al., 2007; Toth et al., 2006). In addition, novelty of symbolic play ideas generated by participants was evaluated in some experiments to reflect their competence in conceiving spontaneous symbolic thoughts that are not suggested by adults. (Charman and Baron-Cohen, 1997; Jarrold et al., 1996; Lewis and Boucher, 1995; Ungerer et al., 1981). Qualitative measurements examine subjects' competence of symbolic play and general play experience. For example, Riguet (1979) used a five-level Likert scale to measure children's attitude and involvement in terms of cooperativeness, interest, attention, smiling and seriousness. Hobson et al. (2009) invited a child psychology expert to rate play aspects in a three-level Likert scale relating to symbolic thought, flexibility, and creativity and fun.

In addition to immediate enhancement during prompted sessions, long-term generalization effect has been explored in previous research, which pertains to maintaining symbolic play behaviours in unstructured contexts. The most common method is pre-post evaluation, which follows the procedure of pre-test of spontaneous symbolic play behaviour, symbolic play training, and post-test of spontaneous symbolic play with the same (Sherratt, 2002) or different play context (e.g. new toys (Ingersoll and Schreibman, 2006; Stahmer, 1995; Thorp et al., 1995), or different people (Goldstein and Cisar, 1992; Kasari et al., 2006)). Generalization is the ultimate goal for symbolic play enhancement, which however requires long-term and systematic training and evaluation. In this study, I intended to evaluate the immediate effectiveness of the proposed AR system in enhancing symbolic play for children with ASC, and take findings as the research foundation for future studies to explore generalization effects of the AR approach. Meanwhile, I attempt to probe evidence of potential skill transfer in symbolic play from the AR scenario to a natural play setting.

The review conducted in this section provides essential guidance for the design and evaluation of the AR system in the following sections. In the system design section (Section 5.3), I apply appropriate play themes in the AR system in response to restricted interests of children with ASC. In the experiment design section (Section 5.6), I explore the use of visual support to guide experiment preparation, procedure, and user feedback collection in order to cope with impaired abilities relating to language and adaptation to change. Furthermore, I adopt existing coding schemes and measurements of symbolic play in this study. In the experiment results section (Section 5.7), I report the system effectiveness, as well as the usability of the AR magic mirror in order to understand the potential impact of fine motor difficulty associated with autism.

5.3 System Design

In this section, I present the design of the AR system that aims to enhance solitary symbolic play for children with ASC. This design process involves (1) applying the AR stimuli proposed in Chapter 3 to illustrate symbolic thought, and help children to form and carry out divergent play ideas; (2) designing primary and imaginary representations based on investigation of restricted play interests of autistic children discussed in Section 5.2; and (3) designing an AR system with the magic mirror display metaphor.

5.3.1 Design of AR Scaffolding

The three-level AR approach proposed in Chapter 3 provides graduated support for the above two goals of the AR system. The level-1 stimulus illustrates the mental processes of a set of pre-defined symbolic thoughts by presenting all three elements associated with it including primary representation (e.g. a block), imaginary representation (e.g. a car), and symbolic transformation from the former to the latter (e.g. overlay a car on the block). It also supports a child to proactively think of play ideas associated with the symbolic thought (e.g. park the car in the garage) without direct instruction as provided in conventional interventions.

In addition to the illustration of symbolic thought and prompting of divergent play ideas, the level-2 stimulus allows a child to actively manipulate the symbolic transformation process by linking an imaginary representation to the primary representation (e.g. the block can be a car or an airplane); while the level-3 stimulus further supports a child to conceive arbitrary imaginary representations to which the primary representation can be transformed to (e.g. form the imaginary representation of a lake and associate it with a disk).

The goal of this study is to develop a proof-of-concept AR system as the first attempt to explore the effectiveness of using AR technologies to promote symbolic play for children with ASC. Since very little is known about how capable autistic children are to interact with physical play objects with an AR magic mirror, I decide to only adopt the level-1 stimulus in this study in order to focus on examining the primary effectiveness of the AR technologies for symbolic play enhancement, and continue exploring more advanced forms of stimuli in Chapter 6 once the positive effect of the proposed AR system is identified in this study.

5.3.2 Design of Primary and Imaginary Representations

Primary Representation

Primary representation pertains to the physical referent in the real world, which seeds the conception of imaginary representation in symbolic play (see Chapter 3). In previous studies, physical objects with simple geometric shapes are frequently used as play materials. This is because unlike normal objects used in daily life (e.g. a cup or clock) these objects are not related with obvious functional features. Research shows that it is easier for young children to associate imaginary representations to physical referents with similar physical dimensions than those with dissimilar dimensions or functions (Elder and Pederson, 1978; Tomasello et al., 1999). When relating an imaginary representation to a dissimilar physical referent, a child has to inhibit the usual response to the original function of the referent object, which is especially difficult for children with ASC due to poor inhibition abilities (Hill, 2004). Therefore, I chose physical objects with simple geometric shapes as primary representations (Figure 5.1), in order to lessen cognitive requirements to transform them to imaginary representations.

The primary representations were divided into two groups: AR objects (Figure 5.1(a)) and non-AR objects (Figure 5.1(b)). AR objects are trackable objects to be overlaid with imaginary representations by the AR system, which include three foam blocks with wood texture and a cardboard box. Non-AR objects are non-trackable objects and included in the AR system to encourage spontaneous object substitutions beyond symbolic transformations illustrated by the AR system. This group of objects includes pen lids, cotton balls, Popsicle sticks, paper

(a) AR objects (b) Non-AR objects

Figure 5.1: The collection of primary representations.

tubes and a piece of felt cloth. Symbolic play involving non-AR objects reflects the potential of children to apply symbolic thought to normal play materials in an AR environment.

Imaginary Representation

Imaginary representation pertains to non-literal representations associated with primary representations in symbolic thought. I chose vehicles as the play theme of the AR system because researchers have observed that autistic children often show an obsessive interest in machinery (see Section 5.2). The purpose is to make use of children's restricted interests to elicit motivation to interact with the AR system, thus increasing the chance to learn mental processes of symbolic thought and form divergent play ideas accordingly. I designed a set of imaginary representations for symbolic transformation in three of the most popular vehicle themes: car, train and airplane.

Each vehicle theme incorporates three tiers of augmentations intended for progressively complex symbolic play (Figure 5.2): (1) the core concept of object substitution between blocks and vehicles (car, school bus, locomotive, train coach, airplane, rescue helicopter); (2) extended object substitution between block/box and vehicle related objects (school, petrol, train station, train light, hangar, airport vehicle lift); (3) pretend properties and imaginary object with more vehicle related objects (bridge, train track, runway, crane) and scenarios (dusty car, fire).

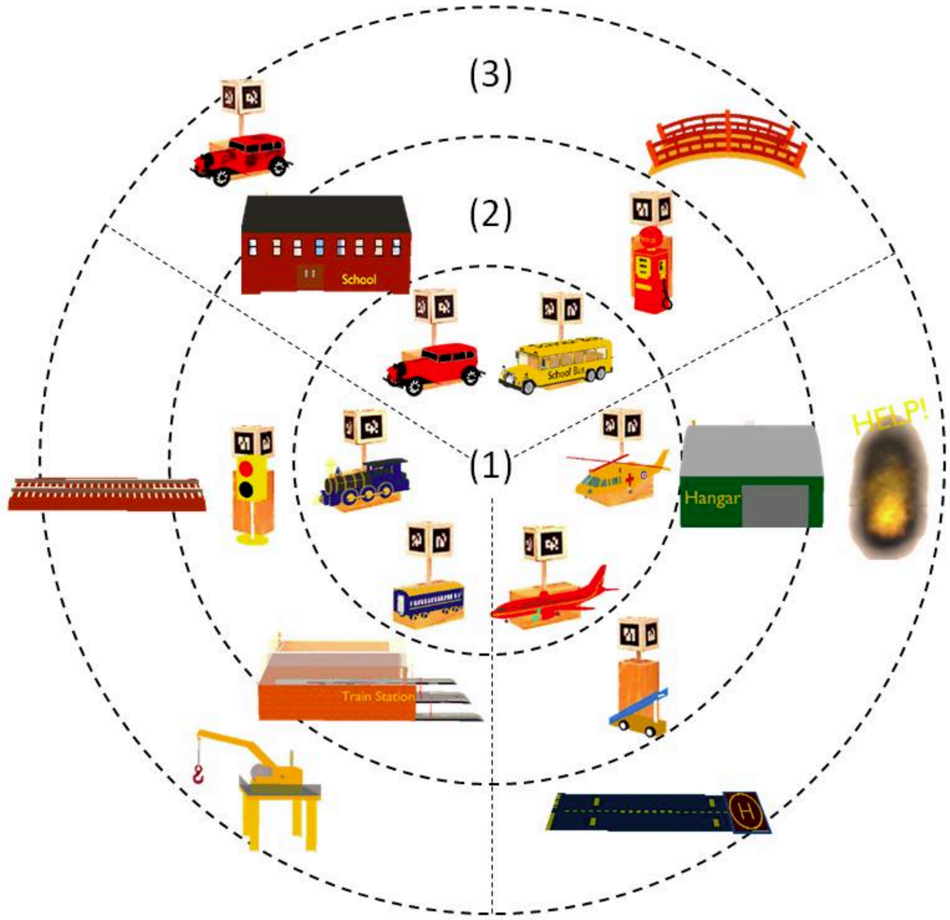


Figure 5.2: Summary of three tiers of imaginary representations: (1) core object substitution; (2) extended object substitution; (3) pretend properties and imaginary object.

The first tier of augmentation was designed to illustrate the fundamental mental processes of symbolic thought by overlaying vehicles on the blocks. Additional visual stimuli were added such as spinning propellers and rotating tires, to encourage children to carry out simple play acts towards the substituted objects (e.g. drive the car on the table). This is because research shows that children with ASC have an obsessive interest with spinning objects (Section 5.2).

The second tier of augmentation was designed to extend symbolic transformation illustration and provide more vehicle related objects to encourage the child to think of and carry out situationally appropriate play ideas (e.g. a train arrives in the train station, or filling the car with petrol). This is different from instructed symbolic play with which specific play ideas are given to the child. As a result, this encourages the generation of play ideas in a diverse and independent way.

The third tier of augmentation was designed to provide further illustration of pretend properties and imaginary objects to encourage more complex vehicle related play ideas. To guide the child to carry out symbolic play in a progressive manner and limit the number of items to which the child attends at the same time, the experimenter can show or hide the third type of augmentation in real-time. This feature was incorporated in the experiment procedure in Section 5.6.3.

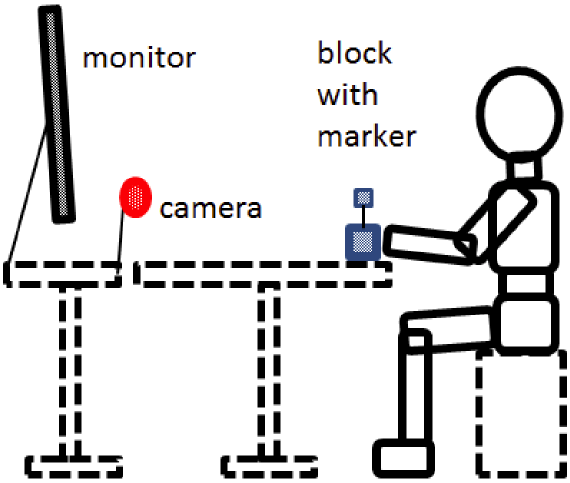
Besides the three tiers of augmentations, I designed additional contextual indications for the purpose of helping children to relate imaginary representations not provided by the AR system to non-AR objects. For example, children were expected to relate the school context (school bus and school house) to students; rescue context (rescue helicopter and fire with cry for help) to people in danger; dusty car to water; and crane to cargo. The above design provided extensions to encourage novel symbolic thought beyond those suggested by the system augmentation. Figure 5.3 shows children interacting with the AR system in these different vehicle themes.

5.3.3 AR Interface with the Magic Mirror Metaphor

The AR system has been designed based on the metaphor of a magic mirror showing reality enriched with AR augmentations, as demonstrated in Figure 5.4. A child looks into the AR interface as if it is a magic mirror which lets them see the reflection of the physical world overlaid with the imagined scene.

I chose the magic mirror as the display metaphor for the AR interface because:

Figure 5.3: Participants interact with the AR system with the car, train and airplane themes.



(a) The profile illustration of the AR system

(b) A participant interacting with the AR system

Figure 5.4: The AR system with the magic mirror display metaphor.

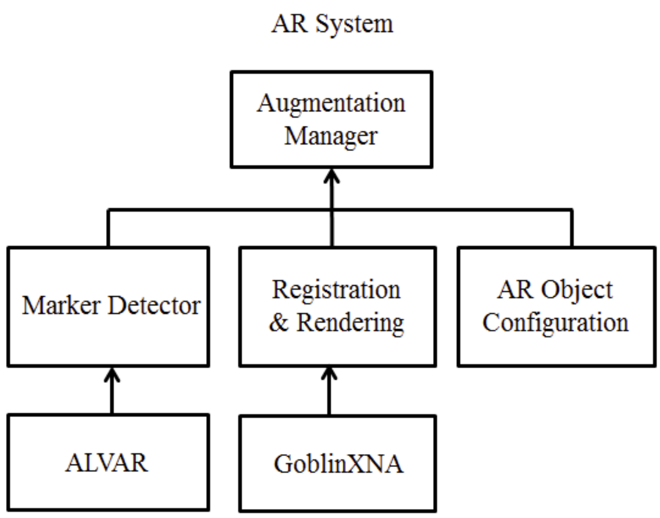
(1) the magic mirror supports all technical considerations for symbolic play including bimanual manipulation, flexible augmentation, and social interaction and it is more accessible than HMD (see Section 2.3.2); and (2) the usability study showed that mirror reversal has only limited impact on the AR magic mirror in supporting complex bimanual manipulation of physical objects (see Chapter 4). In particular, the results in the preparatory usability study suggested that movement non-parallel to the screen should be discouraged in order to avoid confusion relating to mirror reversal. Based on this heuristic, I simplified imaginary representations such as the bridge, train track and airplane runway into a straight line orientated in parallel to the screen.

5.4 System Implementation

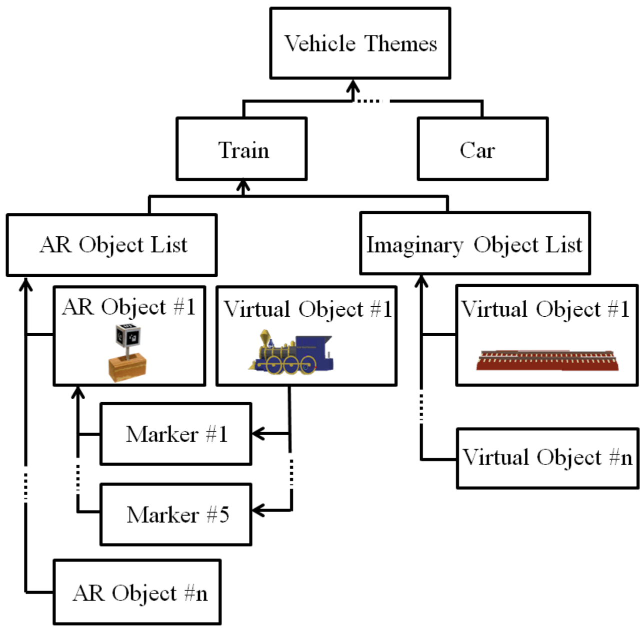
5.4.1 System Components

The AR system is composed of four modules as shown in Figure 5.5(a): (1) Marker Detector: Each AR object is associated with five markers. For each video frame, the "Marker Detector" detects all markers visible in the camera view, and retrieves the position and orientation of the marker with the biggest area for each group of markers associated with the same AR object. This module was implemented based on the open source ALVAR tracking library (VTT, 2011); (2) Registration and Rendering: takes charge of registering and rendering a virtual object with specific pose and location in the three-dimensional AR coordinate system. This module was implemented based on the open source AR library Goblin XNA (Oda, 2011). I applied the double exponential smoothing method (Gardner, 1985) in Goblin XNA to minimize the augmentation jitter issue; (3) AR Object Configuration: maintains a schema of the configuration between physical objects and associated virtual objects; (4) Augmentation Manager: maintains the state of the vehicle themes and obtains AR object configuration information to calculate the pose and location of the virtual object based on the detected marker and its spatial relationship with the virtual object.

The detailed schema of the AR object configuration is illustrated in Figure 5.5(b). The purpose of this design is to allow users to configure the link between virtual and physical objects. The configuration schema contains three vehicle themes (car, train, and airplane). Each theme is composed of two lists of



(a) System modules



(b) AR object configuration schema

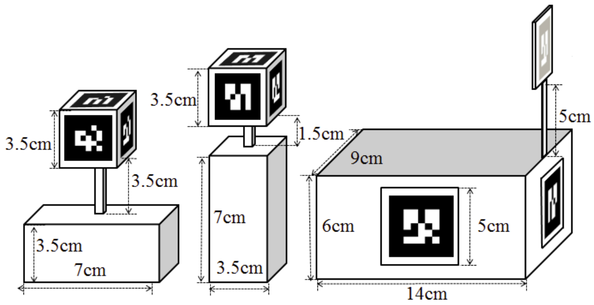
Figure 5.5: System Components.

objects: (1) the AR object list maintains a list of AR objects, each one associated with a fixed number of markers and a virtual object. The list also provides translation, rotation and scale information associated with each virtual object in order to support flexible alignment with an AR object whose marker installation is different from these pre-defined in this AR system; (2) the imaginary object list maintains a list of virtual objects to be augmented on the table surface (e.g. train track). Those virtual objects are statically registered with a calibration marker instead of a physical marker placed on the table in order to avoid occlusion (e.g. occlusion would occur when the child moves a block along the virtual train track). Prior to the experiment the calibration marker was placed in the middle of the table and the AR system recorded its transformation matrix before the marker was removed. In this way, the virtual objects can be registered on the surface of the table properly during the system runtime.

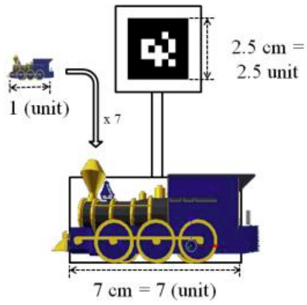
5.4.2 AR Object Tracking

I applied the marker-based method to track AR objects in this study instead of other tracking methods reviewed in Section 2.1.2, because of its flexibility and robustness to track arbitrary objects. Unlike model-based tracking methods that require pre-built 3D models, marker-based tracking can easily extend the choice of objects to be tracked without knowing their 3D features. While hand occlusion often causes loss of tracking with model-based tracking methods, marker-based tracking methods can limit the impact of hand occlusion by offsetting the marker placement from the main body of the target object.

The detailed installation of markers to each AR object is illustrated in Figure 5.6(a). The attachment method is designed to keep a high degree of freedom in tracking and minimize the chance of marker occlusion between these AR objects when aligned in front of the camera. The dimension and position of the virtual object is designed to approximate that of its associated AR object. Figure 5.6(b) illustrates the process of aligning the virtual unit in the 3D modelling environment with the physical unit. The metrics between the virtual world and the physical world are scaled by setting one unit in the AR system equal to one centimetre in the real world. Virtual objects in this AR system were created in the open source 3D modeling software Blender (Blender.org, 2012), and the length of each virtual object along the X axis was always set to one unit.



(a) Installation of markers to each object



(b) The mapping between virtual and physical unit

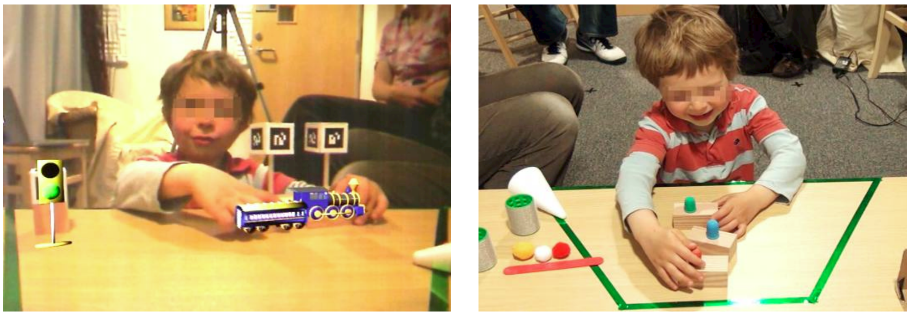
Figure 5.6: The marker installation and unit mapping between physical and virtual objects.

Knowing the length of a physical referent, one can map a virtual object to it by scaling the virtual object by the length of the physical referent, and translate the position accordingly to match the centre of the physical object. All the scale and translation information was defined in the configuration file, which is loaded by the AR system when it launches. This enables the system to automatically adjust the dimension of the virtual object according to the physical shape of its coupled AR object, thus allowing the designers and teachers to extend symbolic transformation illustrations between physical and imaginary objects in the future.

5.5 Pilot Study and Improvements

I demonstrated the AR system to several child psychologists and received much positive feedback. I also brought the system to an autism event organized by the local branch of the National Autistic Society, and two children with ASC aged 3 years 9 months and 2 years 11 months tried out the system. Both children explored the system by manipulating blocks in front of the camera. Neither of them carried out meaningful play due to their young age and severely impaired play behaviours (mainly engaged with sensorimotor play like mouthing or banging). This observation provided insight into the potential user group for which the system is usable.

A pilot study was conducted to test whether typically developing children in



(a) AR condition (b) Non-AR condition

Figure 5.7: A child carries out symbolic play in two conditions in the pilot study.

the target age group could interact successfully with the AR system. The study invited four typically developing children as subjects, in the age group 4 to 5 (two boys, two girls, average age 58.6 months) because children of this age are highly engaged with symbolic play, while potential usability issues of AR systems dedicated for such low age groups remain largely unexplored (see Section 2.3.3). The participants were observed to play in two conditions: AR and non-AR. In the AR condition, the child interacts with the AR system. In the non-AR condition, the child plays with the same set of play materials except: (1) the computer screen is switched off; (2) the AR objects are replaced with identically shaped blocks and a box, all without markers. Figure 5.7 shows one child carrying out play in both conditions.

The subjects had no difficulty performing object manipulation with the AR magic mirror, and they used both hands to perform simple manipulations such as grasping, moving, rotating and positioning an AR object relative to another object (for example parking the airplane in a hanger). They had slightly more difficulty locating augmented objects relative to another object represented entirely virtually, as for example in moving a block visualized as a car over a virtual bridge. I hypothesize that this was due to the absence of haptic feedback and to difficulty with depth perception with the AR magic mirror.

Overall the pilot study confirmed that hand-eye coordination of typically developing subjects as young as four years old is sufficiently developed to enable them to use the AR system. The subjects spent as much time playing in the AR condition as in the non-AR condition and they reported greater satisfaction with

Figure 5.8: A participant exploring the AR system in the familiarisation session.

their play in the AR condition. This observation was supported by feedback from both the participants and their parents.

Several suggestions of improvements to the AR system emerged from our study: (1) I noticed that the AR augmentations presented in the AR system at the time of the pilot study were rather simple to encourage diverse play ideas. To improve this, I added additional situational cues in each theme (e.g. school bus/building, train station, rescue helicopter and fire); (2) One participant in the pilot study was very interested in how virtual objects were shown on the display. Considering that autistic children are likely to be interested in computer technology as discussed in Section 5.2.1, I added a familiarisation session before the main tasks. The participant sees virtual rectangles in different colours augmented on the AR objects (see Figure 5.8). They are then allowed to explore freely for up to five minutes to get familiar with the AR technology; (3) I chose to keep colours consistent for non-AR objects of the same type to avoid colour matching play; (4) I replaced props using "interesting" materials with similar ones made of plainer material (e.g. hair rollers covered by velcro were replaced by kitchen towel rolls, rubber thimbles to pen tops) to avoid simple manipulation out of pure sensory curiosity of autistic children as discussed in the related work section.

5.6 Experiment Design

The goal of the experiment is to evaluate the effectiveness of the proposed AR system in prompting solitary symbolic play for young children with ASC. Given the open-ended design of the proposed AR system, I decided to compare participants' performance of producing symbolic play under the elicitation of the AR system and in a non computer-assisted setting from the following perspectives: the frequency and duration of symbolic play produced in each condition, symbolic play complexity and diversity, participants' play experience, individual differences, and usability of the AR magic mirror interface.

To address the above evaluation goal, I designed a within-subject experiment to examine potential positive effects of the AR system in promoting solitary symbolic play for young children with ASC, compared with a non computer-assisted setup. The experiment consisted of two conditions: AR and non-AR. The order of the two conditions was counter-balanced among subjects. There was a short break between the two conditions. In each condition, there were three tasks and the order was randomized. The null and alternative hypotheses of the experiment were:

- $\mathbf{H}_{0A}$: There is no significant difference in the frequency of symbolic play between the AR and non-AR conditions.

  $\mathbf{H}_{1A}$: The AR system can encourage participants to carry out symbolic play more frequently.

- $\mathbf{H}_{0B}$: There is no significant difference in the duration of symbolic play between the AR and non-AR conditions.

  $\mathbf{H}_{1B}$: The AR system can encourage participants to carry out symbolic play with longer duration.

5.6.1 Participants

The study participants were 12 children formally diagnosed with ASC aged 4-7, 10 male and 2 female. Participants were recruited via the Cambridge Autism Research Centre parent mail-list, the newsletter of the Cambridge branch of the National Autistic Society, and local autism events. The University of Cambridge Ethics Committee approved the experiment. All participants were remunerated with an age appropriate educational gift.

I visited participants' homes prior to the experiment to collect information about their autism and language conditions. It also allowed the participants to

Table 5.1: The summary of participants' information.

	Chronological Age (months)	Verbal Mental Age (months)	CARS2 Score
Mean	82	73*	33.3
SD	11.09	17.82	6.34
Range	53-93	45-104	22.5-41.5

* One participant was not able to complete the BPVS3

get familiar with me as experimenter for the coming study. I used the Childhood Autism Rating Scale, 2nd edition (CARS2) (Schopler et al., 1980) based on parent interviews and direct observation to get an approximate understanding of participants' autism severity. I also evaluated their verbal mental age using the British Picture Vocabulary Scale, 3rd edition (BPVS3) (Dunn and Dunn, 2009) since research indicates that symbolic play of children with ASC is closely correlated with their language comprehension. Table 5.1 shows a summary of the participants' information. The score range of different autism severities is minimal (15-29), moderate (30-36.5) and severe (37 and higher).

Based on the CARS2 parent interview, the level for "object use in play" among participants was between mildly and moderately inappropriate (except one participant who was reported as age appropriate). The levels of symbolic play frequency at home were frequent (3 participants), sometimes (4 participants), seldom (4 participants) and never (1 participant). Nine participants attend mainstream primary and reception class with special assistance. One was being home educated when the study took place. One attends a special school and the other one is in a special class for autism and learning difficulties affiliated with a mainstream school. All participants are familiar with computer devices. Most of them use computers on a daily basis.

5.6.2 Apparatus

The experiment took place in the usability laboratory of the Computer Laboratory of University of Cambridge, which is divided into the experiment room and the observation room with a semi-transparent mirror in between. The experiment room is decorated as a common living room with sound deadening material on the wall. The apparatus in the AR condition included a 24-inch monitor, a Logitech webcam Pro 9000 (field of view 75 degrees), a laptop computer, a

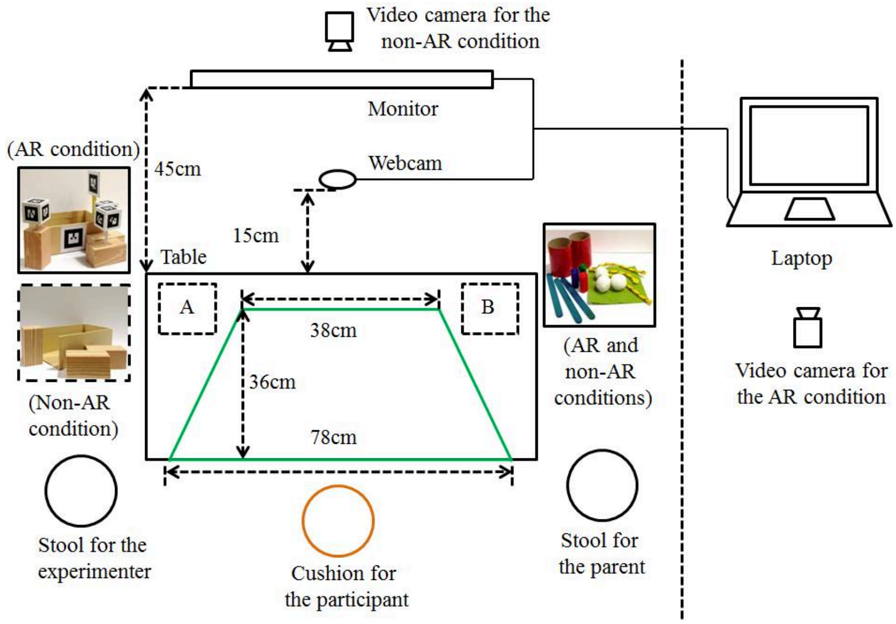


Figure 5.9: The physical setup of AR and non-AR conditions.

mini Bluetooth keyboard, a table (45*90*45cm), and play materials (Figure 5.9). The main parts of the apparatus were deployed in the experiment room. The laptop computer that hosts the AR program and connects to the monitor and webcam was placed in the observation room next door to avoid potential visual and auditory distraction to the participants.

In the AR condition, there were two types of play materials including AR objects (three foam blocks and a cardboard box with markers attached) and a set of non-AR physical props (three cotton balls, two paper tubes, three popsicle sticks, three pen tops, three strings and a piece of cloth). The AR objects were located in area "A" and the non-AR props were located in area "B" on the table (see Figure 5.9). The non-AR setup contained the same table and non-AR props, plus blocks and a box of the same dimensions but without markers located in area "A". In addition, I taped out a trapezoidal area on the table to emphasize the range of the camera view and in both conditions the participants were asked to play within the taped area.

Play materials commonly used in previously mentioned psychology studies include conventional toys that resemble real life objects (e.g. toy vehicles or human figures) and non-toy objects (e.g. pen lids, cotton balls, Popsicle sticks). There is an increasing discrepancy between the literal representation of these conventional toys and non-toy objects, and the pretense representations to which they refer during play. Compared to conventional toys that have high closeness to the real world correspondences, non-toy objects are often used to represent arbitrary objects in symbolic play, which therefore encourage non-literal symbolic transformation such as object substitution (Barton, 2010; Libby et al., 1998; Sherratt, 2002). Research shows that engagement with conventional toys occupies a large amount of time during children's elicited play sessions (Jarrold et al., 1996; Lewis and Boucher, 1995; Ungerer et al., 1981). In order to maximize the support of symbolic transformation within a short period of time while keeping the play props comparable between the AR and non-AR conditions, I did not include conventional toys as experiment materials.

5.6.3 Procedure

Preparation

Prior to the day of the experiment, the parents received a one-page document as a visual guidance with pictorial descriptions of the experiment such as location, room setup, experimenter and rewards. The purpose of the visual guidance is to help parents describe the nature of the study to the participants and make it easier for the participants to adapt to the unfamiliar environment. On the day of the experiment, the parent read and signed the consent form. Then I led the parent and participant to the usability room. The consent form and visual guidance are attached in Appendix B.1 and B.2.

Experiment Procedure

As described in the overall experiment design and apparatus, the experiment contains two conditions (AR and non-AR) and in each condition there are three tasks (car, train and airplane). The main experiment procedures and scripts are consistent in both the AR and non-AR conditions as listed below:

1. A brief introduction: the experimenter reminds the participant to *"play inside of the taped area"*, *"play with anything you like on the table"* and *"stop after 5 minutes"*.

2. Arrange the play materials on the table into a standard initial configuration as shown in Figure 5.9.

3. Start the task: the experimenter holds one block and asks: *"show me how you can play with this block as a car/train/airplane"*, then gives the block to the participant.

4. During the task:

   (a) The experimenter shouldn't give any detailed pretend play ideas.

   (b) If the participant doesn't attend to playing, the experimenter should encourage the child by saying: *"I want to see more how you can play with the block as a car/train/airplane. Let's try some more"*.

   (c) If the participant doesn't use any of the physical props, the experimenter should encourage by saying: *"You can play with anything you like on the table"*.

   (d) The experimenter can prompt a maximum of 3 times. After that the experimenter should ask: *"Do you want to continue with the play or change to another one?"*

5. After 5 minutes, the experimenter should wait until the participant finishes with the current play episode and say *"Very good. Now let's stop and put everything back"*. A 5-minute egg timer was used as the visual support to persuade the participant to stop.

6. Repeat steps 2 - 5 for the other two tasks.

7. Ask the participant for feedback at the end of each condition.

8. Interview the parent when both conditions have finished.

In addition to the procedure above, in the AR condition, the experimenter allowed the participant to try out the AR system in a familiarisation mode prior to the actual task for five minutes. During each task, at around 3 minutes, the experimenter said "*Watch, something will be on the screen*", and then revealed the extra imaginary content (bridge/track/runway) on the screen. At around 4 minutes, the experimenter said "*Watch, something else will be on the screen*", and then switched the imaginary content (dusty effect/crane/fire).

5.6.4 Data Collection

Video Analysis

I analysed participants' play behaviour based on the video footage recorded during the experiment. I set up two video cameras in the experiment, one in front of the participant to record the non-AR session, and one in front of the computer screen in the separate room to record the AR session.

In view of coding schemes applied in research with autism reviewed in the related work section, I designed a coding scheme that includes five play categories: symbolic play, constructive play, relational play, simple play and no play. I excluded functional play because no conventional toy is included in the play material as discussed earlier. The definition and examples of each category are listed below:

1. **Symbolic (Pretend) Play** (PP): Play actions that are either vehicle appropriate or novel, and involve any of the following features:
    - (a) Object Substitution: use one thing as something else (e.g. push the block along the table and make the sound "*choo choo*").
    - (b) Attribution of pretend properties: assign false or absent properties to an object (e.g. make one block talk to another block).
    - (c) Imaginary Object: imagine the presence of something invisible (e.g. use imaginary water to put out the fire).
2. **Constructive Play** (CP): Play actions that involve creating an object or a scene with more than one object (e.g. use tube and block to build a train).
3. **Relational Play** (RP): The participant manipulates more than one object or a single object in relation to others (e.g. combination, stacking, containing and arranging), but not attending to creating something or pretending something meaningful.
4. **Simple Play** (SP): The participant attends to manipulating one object without purposeful meaning (e.g. moving, waving, banging, fingering, mouthing or throwing of a single object).
5. **No Play** (NP): Other actions that are not play related.

I used the video editing tool Camtasia Studio (TechSmith, 2005) to manually annotate: (1) the participant's play actions relating to the play materials; (2) the participant's verbal and vocal utterances; and (3) the experimenter's and parent's talk during the experiment. I coded each action according to the coding scheme. An independent rater who was not aware of the hypotheses was then invited to code 10 out of the total 60 video clips (randomly chosen, 5 from each condition) to verify the reliability of the coding scheme used. The inter-rater agreement was satisfactory (Cohen's kappa = 0.75).

Questionnaires

I used both a parent questionnaire and a participant questionnaire to evaluate the emotional quality of the participant's involvement in each condition. Given the diverse degree of behavioural disturbance of individuals with ASC, it is considered more reliable to have parents rate for engagement rather than the experimenter. Therefore, I asked each parent to observe the participant playing and rate for his or her engagement in terms of cooperativeness, attentiveness and happy smiling (Riguet, 1979) immediately after each experiment session. I also asked the parents to provide overall feedback of the experiment after both sessions were completed. Blank parent and participant questionnaires are attached in Appendix B.2 and B.4. A summary of questions in the parent questionnaire is listed below:

1. Cooperativeness or in-seat behavior (Very Good, Good, OK, Poor, Very Poor)

2. Interest or general attentiveness to the play things (Very Good, Good, OK, Poor, Very Poor)

3. Happy smiling involved in play (Frequent, Sometimes, Seldom, Never)

4. Which session do you think the participant enjoyed more? (First session, Second session, Equal, Not sure)

5. In which session do you think the participant was more engaged? (First session, Second session, Equal, Not sure)

6. Do you think the technology will help to promote pretend play for young children with ASC? (Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree)

7. Do you think the play themes (car, train and airplane) are appropriate? (Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree)

8. Can you name other play themes in the participant's daily play repertoire?

9. Anything you think could be improved for the computer program?

In addition, I asked the participants questions about their play experience and preference. I adopted the Fun Toolkit survey methods (Read and MacFarlane, 2006) in the questionnaire. The detailed questions are listed below:

1. How much do you like the play?

2. One thing you like about the play?

3. One thing you don't like about the play?

4. (AR condition only) Are there other things you want to be on the screen?

5. Which play is more fun (the one with/without screen)? And why?

6. Which one do you prefer to play with your friend (the one with/without screen)?

5.7 Experiment Results

The results of all participants except two are reported in this section. I excluded these two participants' data from the main results because they had difficulty following the experimenter's instructions and were not capable of cooperating during the experiment due to severe impairment in language and joint attention. I will discuss their behaviours separately in the discussion section.

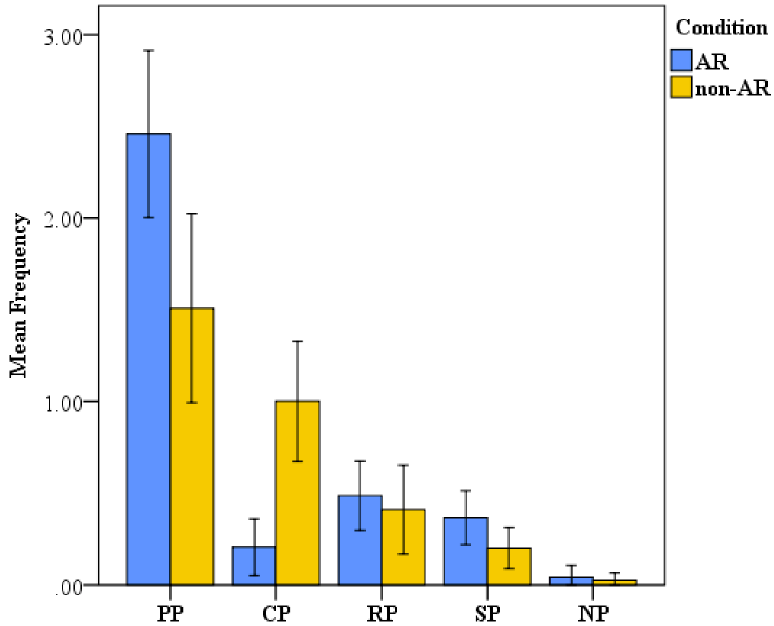


Figure 5.10: Frequency of play action (occurrences per minute) in each category.

5.7.1 Frequency of Play Actions

The frequency of play actions in each play category among participants is normally distributed. The distributions of mean play frequency (occurrences per minute) in each play category are shown in Figure 5.10.

We can see that the mean frequency of symbolic play is higher in the AR condition, while the mean frequency of constructive play is higher in the non-AR condition. The figure also shows that the level of relational play, simple play and no play remains similar in both conditions. I conducted a paired t-test evaluation and found there is a significant difference in the frequency of symbolic play ($t(9) = 4.66$, $p = 0.001 < 0.01$**) and constructive play ($t(9) = -4.91$, $p = 0.001 < 0.01$**).

To explore one indicator of the quality of symbolic play actions produced in both conditions, I further excluded symbolic play actions with repeated play ideas. The result shows that there is still a significantly higher frequency of symbolic play ($t(9) = 2.41$, $p = 0.04 < 0.05$*) produced in the AR condition ($Mean = 1.79$, $SD = 0.68$) than the non-AR condition ($Mean = 1.23$, $SD = 0.63$).

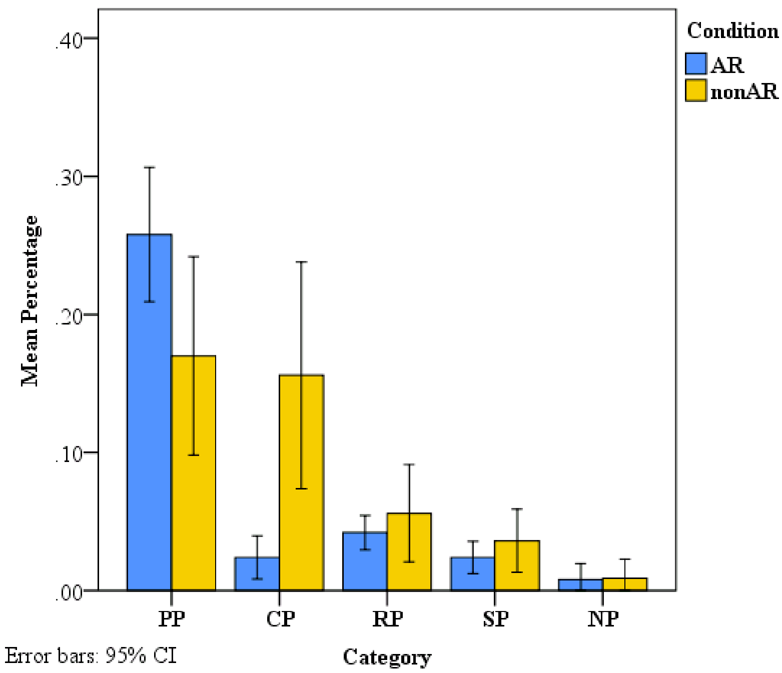


Figure 5.11: Percentage of play time in each category.

5.7.2 Duration of Play Actions

The percentage of time spent in each type of play is illustrated in Figure 5.11. As with the play frequency results, the percentage of time that participants spent in symbolic play is significantly higher ($t(9) = 3.25$, $p = 0.009 < 0.01^{**}$) in the AR condition, while the percentage of time in constructive play is significantly higher ($t(9)$ = -3.49, $p = 0.007 < 0.01^{**}$) in the non-AR condition. The differences among relational play, simple play and no play between the two conditions remain non-significant.

5.7.3 Engagement and Enjoyment

The mean scores of attentiveness and cooperativeness are between ok and high in both conditions, while the appearance of happy smiling for the children is between sometimes to frequent (Figure 5.12). There is a marginally significant difference in happy smiling (Z = -1.90, p = 0.058) using the nonparametric Wilcoxon signed-rank test. According to the parent questionnaire, eight out of

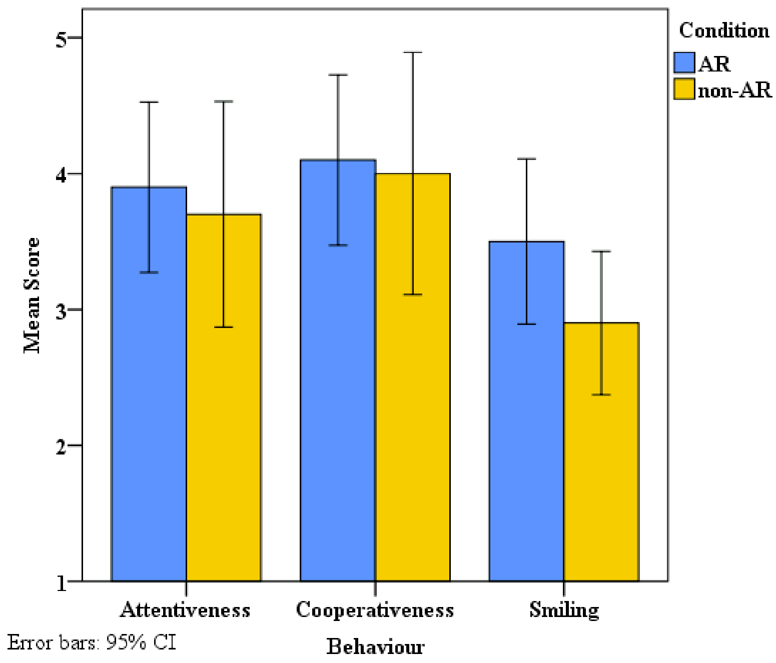


Figure 5.12: The mean score of participants' engagement.

ten parents thought their children were more engaged in the AR condition. One parent thought the participant was equally engaged in both conditions and one thought the participant was more engaged in the non-AR condition. Moreover, I counted how often the experimenter gave verbal prompts ("*show me how to play with the block as a* ...") to encourage the participant to carry on with playing. The experimenter made significantly more verbal prompts (Z = -2.61, p = 0.009 < 0.01**) in the non-AR condition (*Mean* = 0.44) than the AR condition (*Mean* = 0.26) according to the nonparametric Wilcoxon signed-rank test.

The parents' feedback about participants' enjoyment is aligned with their engagement. The same eight parents thought their children enjoyed the play more in the AR condition. The average score for enjoyment is good in the AR condition and really good in the non-AR condition according to the participants' feedback. Comments about things participants like and dislike in each condition are summarized in Table 5.2.

Although the enjoyment score was higher for the non-AR condition, when

Table 5.2: The summary of participants' feedback of like and dislike of each condition.

Condition	Feedback	
	Like	Dislike
AR	"a different picture on the block" "when the car gets rusty" "car get into a school" "flying" "they all change into different things" "the airport"	"the train push a lot of things off the table" "no police car"
non-AR	"when the goodies win" "the party" "make a lot of things using the blocks" "can rescue the car in a box" "shop keeper" "make the airplane crash"	"the baddies broke the plane" "there is no police car, no train station" "didn't know what to do" "the toy doesn't have eyes"

asked which one is more fun, nine out of ten participants chose the AR system and indicated that they would prefer the AR system to the non-AR system for play with friends. Reasons explained by the participants include: "The blocks become into different things", "It has a picture", "can see things that is not actually there", "I like seeing myself", and "It's funny".

5.7.4 Relevance to Suggested Play Themes

During the experiment, I noticed that the themes of symbolic play carried out by the participants varied between AR and non-AR conditions even though the participants were asked to carry out the same vehicle theme at the beginning and during each task. To investigate the difference of attending to the vehicle theme indicated by the experimenter, as well as details of play ideas in terms of realistic and novel among those complying with the vehicle theme, I further categorized symbolic play actions into three types:

1. **Relevant_Reality**: Actions that approximate realistic behavior of the vehicle which are situationally appropriate.
2. **Relevant_Novel**: Actions that involve the vehicle but are novel instead of realistic.

Table 5.3: The summary of participants' play ideas in terms of relevance to the suggested vehicle theme.

Relevant		Not Relevant
Realistic	Novel	
move the car along the table; move the train into the train station; make the airplane take off from the runway; point the stick at the dusty car and say "water"; put a cotton ball on the train and say "driver"; make a tapping motion around the car with his/her finger and say "fix the car"; move the train over a stick and say "train track"	move the car in the air and say "climb a tree"; make cotton balls hit the cars and say "angry bird"; make the car "go through" a tube and say "in the black hole"; make a tapping motion around the train with a string and say "poison the train driver"; point the two airplanes at each other and say "how's it going"	party; spaceship fight; shopkeeper; monster;

3. **Not relevant**: Actions that do not involve the vehicle theme indicated by the experimenter.

Table 5.3 shows examples of representative play ideas. The mean percentage of symbolic play actions in each play theme category in the two conditions are shown in Figure 5.13. The mean percentages of total relevant actions including both reality-based and novel-based is significantly higher in the AR condition according to the paired t-test ($t(9) = 2.84$, $p = 0.02 < 0.05$). The inter-rater agreement of two raters is satisfactory (Cohen's kappa = 0.85).

5.7.5 Individual Differences in Symbolic Play

Since autism is a pervasive developmental condition, there is a significant diversity of individual difficulties as discussed in the related work section. In order to get an insight into the effectiveness difference of the AR system in supporting autistic children with different degrees of symbolic play impairment, I analysed the symbolic play over time and use of non-AR objects of each individual participant during the experiment.

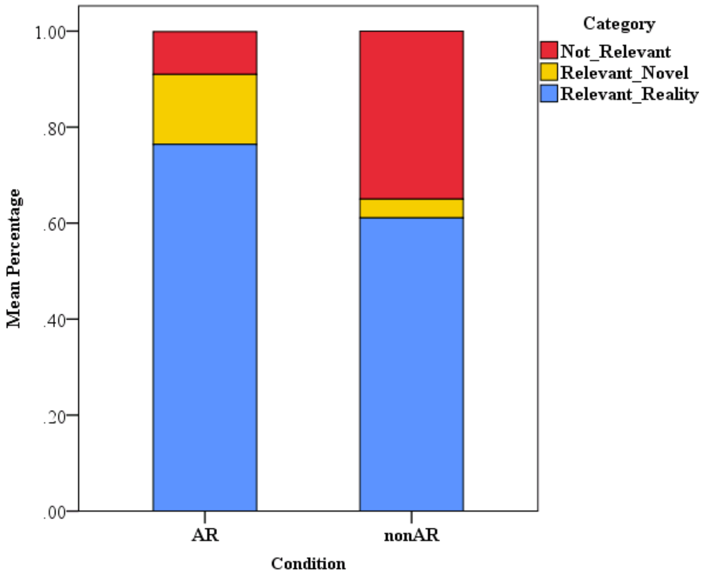


Figure 5.13: The percentage of symbolic play actions in each theme relevance category.

Symbolic Play over Time

In order to further investigate individual participants' symbolic play behaviours in each condition, I calculated the average symbolic play occurrence of all ten participants (P1-P10) at one minute intervals during the first five minutes of each of the three tasks (Figure 5.14).

Overall, the participants' symbolic play behaviour can be separated into three groups: (1) for P3, P5 and P9, there is a consistent trend that they produced more symbolic play in the AR condition than the baseline non-AR condition throughout the task; (2) for P4, P6, P7, P8 and P10, they produced more symbolic play in the AR condition than the non-AR condition during the majority of the five minutes' period; (3) for P1 and P2, the relative extent of symbolic play actions was interleaved between conditions. As to play consistency, the symbolic play produced over the five minutes' period in the AR condition remains relatively steady for the majority of participants. This could be related to the addition of new augmentations to the scene at three and four minutes respectively to keep the participants developing play ideas. P6 and P10 were two exceptions who produced much more symbolic play than both the average level among participants in the

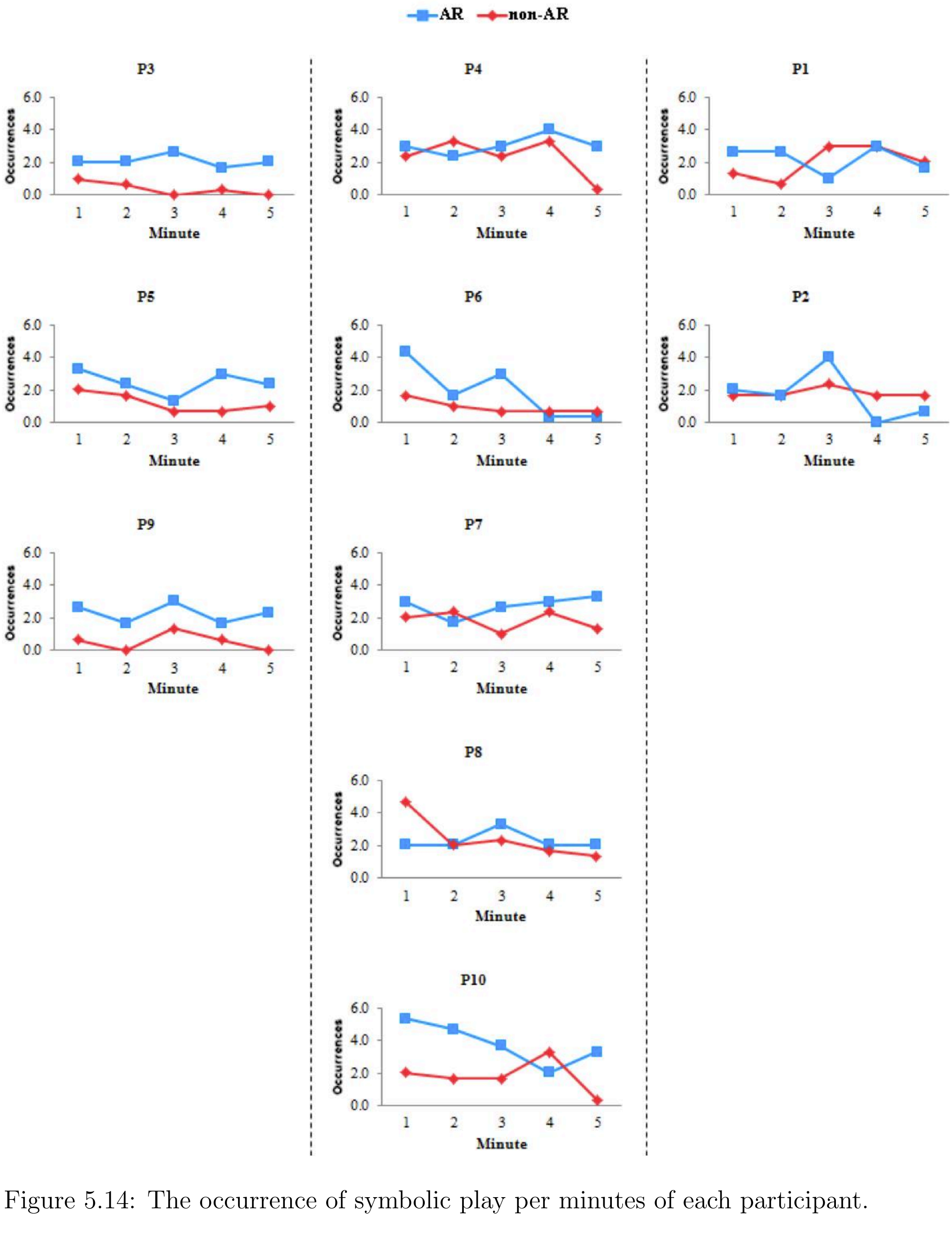


Figure 5.14: The occurrence of symbolic play per minutes of each participant.

AR condition and the corresponding non-AR condition at the start of play, with the amount of symbolic play decreasing over time. Such intense concentration of play episodes in the early period may exhaust play ideas quickly, thus making it difficult to maintain the relatively high level throughout the task. More factors of individual differences will be discussed in the discussion session.

Non-AR Object Use

The usage of non-AR objects is an important indicator of applying independent symbolic thought to play materials beyond those illustrated by AR augmentations. For example, in the AR condition a participant put Popsicle sticks close to the block augmented with a dusty car representation and made the sound of water spraying. Another example in the non-AR condition is when a participant put cotton balls on a block as if they were passengers on the train. The number of original symbolic play ideas generated by each participant involving non-AR objects is shown in Figure 5.15. For P3, P4, P6, P7, P8 and P10, more non-AR object play ideas were produced while using the AR system. For P5 and P9, there were an equal number of ideas involving the use of non-AR objects. For P1 and P2, more play ideas were created in the non-AR condition, but most of these were irrelevant to the play theme suggested by the experimenter.

There was concern prior to the study that the salient visual effect of the AR augmentation may capture too much of the children's attention such that they will pay little attention to non-AR objects. The results show an intriguing integration between AR and non-AR objects in an open-ended AR play scenario. Since non-AR objects will still be accessible when the AR augmentations are switched off, symbolic play experience with these non-AR objects under the elicitation of the AR system is more likely to be generalized into natural play settings.

5.7.6 Effect of the Condition Order

I conducted the experiment in a counter-balanced manner since the play materials and play themes are shared between the AR and non-AR conditions. In this section, I look into the interaction effects of condition and order on the frequency of symbolic play and constructive play respectively. From Figure 5.16(a) we can see that for participants who went through the non-AR condition first and then AR condition, they clearly tend to produce more symbolic play in the AR condi-

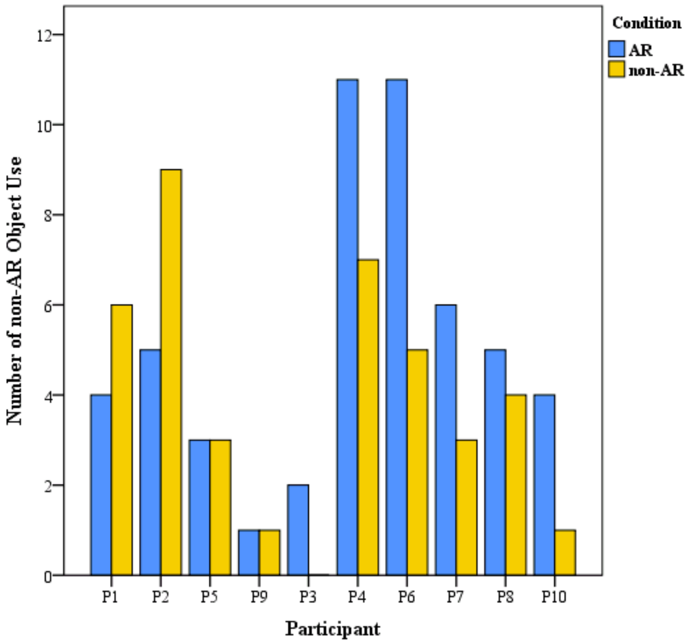
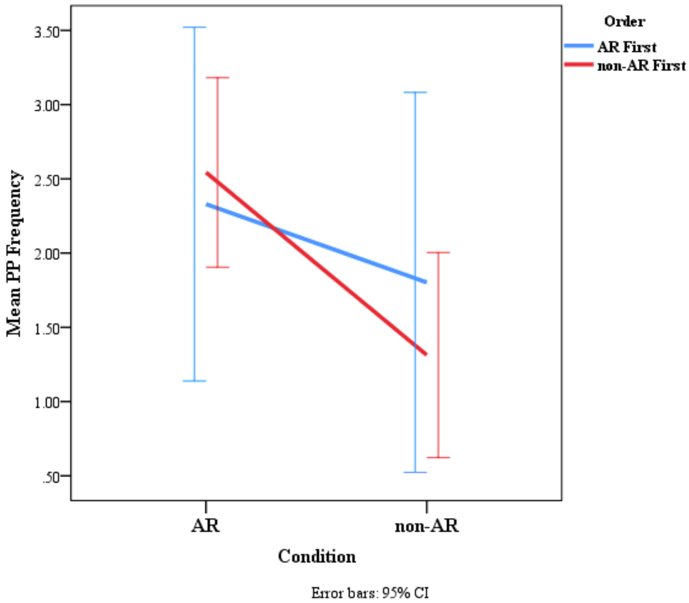


Figure 5.15: The number of non-AR object uses of each participant.

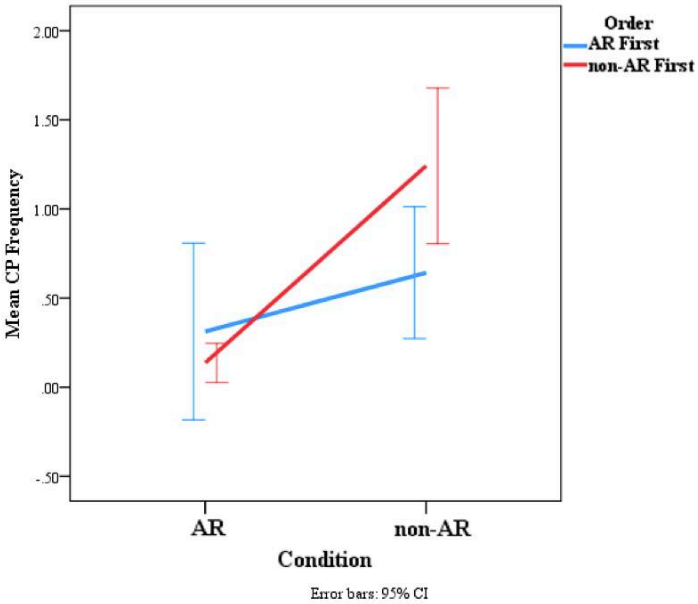
tion. For those who did the AR condition first, the mean frequency of symbolic play produced in the AR condition is also higher than the non-AR condition, however such difference is weaker distribution wise. As a result the interaction effect is not significant ($F(1,16) = 1.24$, $p = 0.28 > 0.05$). Figure 5.16(b) shows that constructive play in the non-AR condition tends to decrease when the participants used the AR system first and there is a significant interaction between condition and order for constructive play ($F(1,16) = 8.40$, $p = 0.01$).

5.8 Discussion

In this section, I discuss major findings of the experiment results including the effectiveness of the AR system, participant engagement, individual differences in elicited symbolic play, potential skill transfer and excluded cases. In addition, I discuss the usability of the magic mirror interface in supporting physical object manipulation during play, adapting the AR system in an intervention context, reflections on experiment design, and limitations and future work of this study.



(a) Condition order effect with symbolic play



(b) Condition order effect with constructive play

Figure 5.16: The effect of the condition order with symbolic play and constructive play.

5.8.1 Effectiveness of the AR System

Quantity of AR Elicited Symbolic Play

The experiment results support the theory that children with ASC can carry out symbolic play under elicited prompts (see Section 2.2.2). In particular, the results reject both null hypotheses in this study and show that there is a significantly higher frequency and duration of symbolic play in the AR condition than the non-AR condition. This indicates a positive effect of using AR technologies to promote symbolic play for young children with ASC.

Results also show that symbolic play actions surpass other types of play in both conditions. This may be largely due to the non-functional feature of the experiment materials. On the other hand, participants tend to produce more constructive play in the non-AR condition. This can also be related to the non-functional feature of the play materials, which supports building things up in addition to pretending. Meanwhile in the AR condition, the salient visual indications given by the AR system are more persuasive for symbolic play than constructive play.

Quality of AR Elicited Symbolic Play

I analysed the details of AR elicited symbolic play to further investigate the complexity and diversity of symbolic play produced with the AR system.

First, there is a noticeable difference in how participants followed the elicited play theme in each condition. As shown in Figure 5.13, in the AR condition symbolic play actions carried out by the participants were highly relevant to the vehicle theme indicated by the experimenter at the beginning of each task. In the non-AR condition, participants tended to carry out less relevant themes. In some extreme cases, the participants ignored the experimenter's suggestions and carried out irrelevant themes (e.g. spaceship, party, shopkeeper, etc.) consistently across tasks. Such intense and inflexible play preference is largely due to participants' restricted play interests. It is, therefore, difficult for typically developing peers to join symbolic play with an autistic child, where plots are often strictly copied from things seen in movies, games or on TV, as many parents reported in this study. The inclination of following play themes with the AR system can make it a promising platform to support and regulate shared symbolic play among autistic children and their parents or peers.

Second, participants produced diverse symbolic play ideas relating to the indicated vehicle theme. In particular, the proportion of novel ideas to situationally appropriate ideas is relatively high in the AR condition. This is a very interesting result because children with ASC are constantly found to lack novel pretend acts compared with matched control groups due to executive deficit in generating novel ideas (Charman and Baron-Cohen, 1997; Jarrold et al., 1996). This result confirms the effect of the level-1 stimulus of the three-level AR approach proposed in Chapter 3, as well as the design of the three-tier imaginary augmentation to elicit divergent play ideas (Section 5.3.1). In addition, by visualizing symbolic thoughts involved in the suggested vehicle theme, the AR system lessened participants' mental efforts which may help them better retrieve general knowledge in the central cognitive system in order to conceive relevant play ideas (see Section 3.1.2). For example, one participant commented about the AR system as " [I] can remember what I might need".

5.8.2 Engagement

The participants' engagement was high in both setups, which could be related to the structured nature of the experiment. Parents' feedback shows that participants were more engaged in the AR condition. In addition, the lower frequency of the experimenter's verbal prompts also indicates that participants were more engaged in the AR than the non-AR condition. Although the system familiarisation session at the beginning of the AR condition is meant to reduce the novelty effect of the AR technology, it is still likely to be one of the motivational factors during the experiment. This is further indicated by the result that the majority of participants thought that the AR session was more fun and would prefer to play it with their friends. In short, the high engagement suggests the AR system as a favourable scaffolding to increase children's motivation for symbolic play, which is often lacking in free-play environments (see Section 2.2.2).

5.8.3 Individual Differences

As discussed in the related work section, individuals show different levels of deficit under the autism spectrum, and difficulty with sharing imaginative play is only one of the many autistic symptoms. This makes the "one treatment for all" approach almost impossible. Nevertheless analysing the individual performance difference helps us obtain a better understanding of the potential user group that will benefit most by using the AR system to improve symbolic play. The combined results of symbolic play occurrence over time and use of non-AR objects indicate an interesting pattern among the participants, which is elaborated below.

P3, P5, and P9 seldom engage with symbolic play at home according to the parent questionnaire and interview. During the experiment, all of them consistently produced more symbolic play during each one minute interval in the AR condition than the non-AR condition. This result indicates that the AR system has the most positive effect upon participants who have the most developmental delay in spontaneous symbolic play. In terms of non-AR object usage, they produced equivalent or more symbolic play involving non-AR objects in the AR condition, but fewer in total compared to the other participants. Since the use of non-AR objects closely reflects children's symbolic play ability in a natural setup, this further suggests that although the AR system has an immediate effect on eliciting symbolic play for children with severely impaired symbolic play, it remains challenging to help them generalize symbolic thought to non-augmented play materials.

P1 and P2 show frequent symbolic play at home according to the parent questionnaire and interview. During the experiment they showed a minimal difference in symbolic play produced per minute in the AR and non-AR conditions and they tended to develop more symbolic play ideas involving non-AR objects in the non-AR condition. The major play behavior in common between P1 and P2 is that in the non-AR condition, both of them carried out the same theme repetitively throughout the three tasks regardless of the vehicle-related theme suggested by the experimenter. This is consistent with parent reports that their symbolic play at home is usually limited to what they saw on TV and they often have difficulty to play with other children due to theme or plot conflicts. On the contrary in the AR condition they tended to adapt to the theme switching and produce more theme-relevant play ideas than in the non-AR condition. These results imply that the AR system may help autistic children who tend to engage with symbolic play in their daily repertoire but with a very narrow range of play interests to adapt to new themes.

For the remaining five participants, four of them were reported to occasionally carry out symbolic play while the remaining one was reported as "frequently". Results show that they produced overall more symbolic play in the AR condition during the five minute period, although this pattern is less consistent than those with severe symbolic play impairments. In addition, there is an apparent improvement of use of non-AR objects in the AR system. It shows a potential positive effect of the AR system to encourage participants to transfer symbolic thought to non-AR objects with the majority of the participants under a short exposure.

In sum, the above results indicate that there is a relationship between the severity of symbolic play deficit and the effectiveness of the AR system. The AR system shows the most effect in symbolic play enhancement for children with severely impaired symbol play and the least effect for children with minimal symbolic play impairment. For children with moderate impairment in symbolic play, the AR system shows a clear effect on symbolic play enhancement. In addition, the AR system showed promising results in helping children to adapt to different play themes in spite of their restricted play interests. Considering the small sample size of the experiment, knowledge of effectiveness difference of the AR system among children with different levels of symbolic play impairment is informative to predict intervention outcomes using relevant technologies on a larger population.

5.8.4 Potential Skill Transfer

Results show that participants who use the AR system first tend to be less engaged with constructive play activities in the non-AR condition, which suggests that one potential effect of the AR system is to discourage constructive play and guide the participants' attention to symbolic play acts. On the other hand, there is an inclination that participants produced obviously more symbolic play using the AR system when they followed the order from non-AR to AR condition. This tendency of symbolic play increase in the AR condition, however, gets disrupted among participants who were introduced to the AR system first. The most likely explanation is that participants' symbolic play behaviours in the non-AR condition are positively influenced by the AR system, thus the symbolic play difference between the two conditions was eliminated to a noticeable extent. Although we have to be careful when interpreting potential skill transfer since such interaction effect did not reach statistical significance, these results are still informative for future studies involving larger sample sizes and long-term intervention evaluation.

5.8.5 Insights from the Excluded Cases

We have excluded the results of two participants because their engagement for the experiment was too low to be valid. Both of the participants have severe impairment in language, joint attention and object use in play. The first participant managed to attend to and manipulate the AR objects in some vehicle appropriate ways in all three tasks in the AR condition, but produced fewer actions in total compared with other participants and spent most of the time engaged in simple play or no play, such as banging blocks on the table, wandering around the room, and lying on the floor. In the non-AR condition, the participant did similar simple and non-play actions except without any symbolic play in spite of constant prompting from the experimenter and parent.

The second participant could not finish the BPVS3 test due to severe impairment in joint attention. In the AR session, the participant spent most of the time watching the self-image on the screen. When the participant manipulated the AR object, it was rather immature including mouthing, banging and ordering. In the non-AR session, the participant paid little attention to objects on the table and ran away several times out of the experiment room. The observation shows the challenges of designing computer systems for children near the lower end of the autism spectrum.

5.8.6 Usability of the AR System

The experiment showed that participants with ASC aged 4-7 can successfully interact with the AR system. Despite fine motor difficulties reported by most parents in this study, participants were capable to carry out bimanual manipulation with play materials with the AR system. This confirms the feasibility of using the AR magic mirror to support solitary symbolic play for young children with limited visuomotor abilities.

In particular I investigated children's eye-hand coordination with detailed actions involved in object manipulation based on the post-analysis with the experiment video footage (Table 5.4). I divided object manipulations into single and relational object manipulation depending on the number of objects involved. In single object manipulation, a child grasps, translates, or rotates one AR or non-AR object. In relational object manipulation, a child manipulates one object in relation to another (e.g. move/combine/contain one object towards/with/in another object). Participants' main visual attention was divided into three groups: screen, between screen and table, and table. When a child grasps an object, he or she tends to take a quick glance at the object on the table, and then monitor the grasp action from the screen. When a child manipulates a single object or relates it to another object, he or she mainly looks at the screen for visuomotor feedback. The exception case is when a child manipulates non-AR objects with each other, he or she tends to mainly look at the table.

Type	Action	Object 1	Object 2	Attention
Single	Grasp	AR or non-AR	N/A	Table and Screen
	Translate, Rotate	AR or non-AR	N/A	Screen
Relational	Translate, Rotate, Combine, Contain	AR	AR	Screen
		AR	Non-AR	
		Non-AR	AR	
		Non-AR	Non-AR	Table

Table 5.4: Summary of eye-hand coordination with different object manipulation actions.

The above observation reveals that a child tends to rely on the world coordinate system to grasp an object and then shift to the AR magic mirror coordinate system to monitor the manipulation action. In addition there are intermittent attention switches during the manipulation when complex spatial relationship is involved such as combining and containing. Moreover, when moving an object in relation to an AR object without physical referent (e.g. a virtual bridge registered in the middle of the table surface), a child tends to spend extra time exploring the spatial relationship in order to make proper alignment (e.g. move the car across the bridge). Extra efforts with certain relational manipulations under the magic mirror coordinate system reflect potential perceptual disorientation with inward/outward movements under the mirror view as discussed in Section 4.2.3.

Overall, the observation shows that the AR magic mirror can efficiently support young children with ASC to carry out bimanual manipulations with physical objects during symbolic play. They are able to adapt visuomotor abilities to the magic mirror coordinate system for most manipulations, but occasionally refer to the world coordinate system to observe spatial relationship due to the inward/outward mirror reversal. Besides usability involving visuomotor skills under the magic mirror view, I identified additional usability issues as below:

1. Hand over marker: Participants were told to hold the block instead of the marker cube when manipulating the AR object during the familiarisation session. Even under physical prompting, some participants persevered with holding the marker cube which caused the virtual object to flicker. This is likely to be related to restricted behaviour of children with ASC since it did not occur among typically developing children in the pilot study.

2. Limited size of play area: The taped play area can be crowded when it is occupied with AR and non-AR objects. In addition, I needed to put play materials outside of the play area to make it clear at the beginning of each task. This caused the play materials to be invisible in the AR magic mirror and hinders participants from fetching these objects without switching attention to the table.

These usability issues are trade-off results to acquire high tracking accuracy and extensibility, as well as avoid occlusion of placing a marker on the table. For the second issue, it may be improved by drawing a physical marker (e.g. a dot) on the table to indicate the centre location of the virtual objects, and include virtual objects registered on the table surface in the familiarisation session.

5.8.7 Adapting the AR System to the Real World

The current AR system is designed as an experimental apparatus. Therefore, it only provides a small set of AR augmentations and three fixed play themes. Although preliminary results show a positive effect compared with the non-AR condition, further improvements are needed in order to help symbolic play development beyond the laboratory setup. Some improvements are proposed below based on direct observation and questionnaires:

1. Provide more AR augmentations: Most children with ASC have a very restricted range of play interests. Therefore the availability of their desired play theme can be an important motivation. The participant and parent

interviews provided a rich set of play themes that might also be included, such as superheroes, dinosaur, people, baby, police car/office, ship, animal, emergency vehicle, and characters from popular films/games/TV programs.

2. Fade out visual effect: In order to gradually bridge the symbolic play experience from the AR environment to real life scenarios, a fading out mechanism could be implemented for the visual stimuli, which is based on the most-to-least prompt strategy commonly used in the applied behavioral approach (Barton and Wolery, 2008; Doctoroff, 1997; Goldstein and Cisar, 1992).

3. Enable the user to record the play: Recording is a common feature for storytelling systems (e.g. Ryokai, 1999). Several participants in the experiment in their spare time browse online videos for game demonstrations (e.g. Minecraft, Super Mario) and two participants particularly mentioned that they would like to share the play they made in the AR condition online with other children.

5.8.8 Reflections on Rigorous Evaluation

The experiment design presented in this study show a rigorous approach of how to make use of psychology literature in both symbolic play deficit and autism-related symptoms to guide the design evaluation of the AR system (Figure 5.17).

First, the experimental measures applied in previous psychology studies provide rich references to accurately evaluate both quantity and quality of symbolic play in an elicited condition. Second, since ASC is a heterogeneous condition that pervasively affects a child's behaviours, integrating these deficits into the evaluation of the AR system becomes critical to increase the chance of engagement with the AR play scenarios and minimize potential adversities for children to participate in controlled experiments. I summarized a list of autism-specific considerations in this study when designing AR systems and experiments for children with ASC:

Restricted Interests and Activities:

1. Mitigate obsessive interest with computers: autistic children often become interested with how computer systems work due to their interest in general machinery. In the experiment of this study, I designed a familiarization

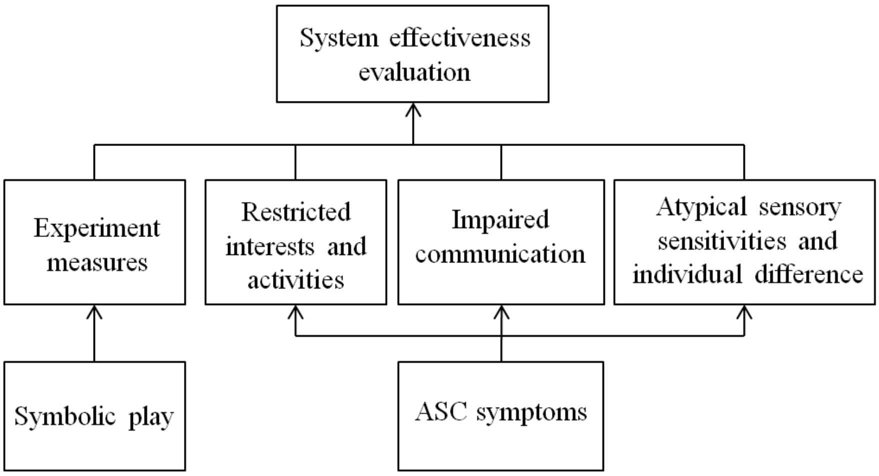


Figure 5.17: Using psychology literature to guide rigorous evaluation for AR systems.

session to allow children to explore the augmentation mechanism of AR technologies before they started the actual play session. In addition, I deployed the laptop computer in a separate room in order to avoid unnecessary distraction during the experiment.

2. Visual supports for change adaptation: most children with ASC follow a strict routine for daily activities and easily become anxious when a new activity is introduced for example when visiting an unfamiliar environment. In order to eliminate withdrawal caused by the above reasons, I decided to meet the participants before the study by running a home interview, so that the participants can become familiar with the experimenter ahead of time. I also prepared visual support to help the parents describe the study to their children and guide the participants through the task transfer. During the experiment, I used an egg timer to remind the participant to stop by the end of each of the 5-minute task sessions. No obvious difficulty of participants to follow the experiment procedures (e.g. refusal to enter the usability room, nervousness, shyness, or refusing to stop playing) was observed and from parents' feedback such visual supports were very helpful.

Impaired Communication:

1. Predict likelihood of participation: it is difficult to explain things like how to interact with the AR system and what one is expected to do during the experiment, to children whose language and joint attention are severely impaired. Therefore researchers have to carefully determine the threshold of communication abilities that candidates have to reach in order to participate in the study. Besides keeping the experiment instructions simple as suggested for experiments involving general child participants, it is also preferable to get direct feedback from caregivers in advance to make sure they are comprehensive to their children.

2. Fun Toolkit: In this study I use questionnaire methods from the Fun Toolkit to collect child feedback with their play experience. The results show that children with ASC as young as four years old can communicate their opinions through the visual support of Fun Toolkit, which is generally used for much older autistic children in previous research.

Additional Atypical Sensory Sensitivities and Individual Difference

1. Impact of other atypical sensory sensitivities: In this study, I considered other pervasive atypical sensory sensitivities of individuals with ASC including touch (remove non-AR objects with intriguing materials), auditory (remove background noise by moving the laptop to another room), fine motor (usability investigation) during the system and evaluation design phases.

2. Evaluate individual differences in performance: As discussed in the related work, it is fruitful to explore differences in individual performance during the experiment, which helps predict the outcome of relevant intervention in a larger population with different subgroups of individuals. In this study, I analysed individual differences of symbolic play over time and object use respectively. The results show a gradual effectiveness of the AR system on children with different levels of symbolic play deficits, and also help identify additional strengths and weaknesses for future investigation.

In sum, helping users to develop certain cognitive skills is much more complex than guiding them to complete a series of procedural actions. It is even more challenging to achieve such goals for children with special needs due to their atypical and diverse developmental abilities. Therefore a thorough literature review on the theory of the target cognitive skills and relevant symptoms of the special user group is required during the design phase for evaluation of the computer system. This underlying approach can be generalized to future systems with different enhancement goals and user groups.

5.8.9 Study Limitations and Future Work

While the study has shown immediate effectiveness of using the AR system in promoting symbolic play for young children with ASC, there are several limitations that should be addressed in the future.

First, the study has limited focus on examining the generalization effect of the AR system, which requires a longer exposure to the AR system associated with pre- and post-test of symbolic play carried out in a free-play environment. Preliminary results of both imbalanced differences of elicited symbolic play between the AR and non-AR condition in different orders, and increased nonliteral use of non-AR objects in the AR condition indicate a potential skill transfer from the AR condition to the non-AR condition. Together with the immediate effectiveness of the AR system in promoting symbolic play, findings of this study motivate future research involving long-term study and bigger sample sizes.

Second, there is a lack of symbolic play comparison between autistic children and typically developing children matched in language abilities. I did not include typically developing children in the formal evaluation of the AR system because an insignificant symbolic play enhancement with typically developing children was observed in the pilot study. Had schedule and resources permitted, such a comparison would have been beneficial to help identify distinct play and system interaction behaviours of children with ASC, thus providing more in-depth information for the design of future AR systems.

Third, the experiment did not include any conventional toys as play materials (e.g. toy vehicles) intentionally to guide children's attention to symbolic transformation in play. As functional play is an indispensable play form in a natural play setting, it will be rewarding to extend the current study with conventional toys in order to obtain a comprehensive understanding of the engagement and quality of AR elicited symbolic play with the presence of conventional play materials.

Fourth, both the pilot and formal experiments showed that it is difficult for autistic children with severe impairments in language, joint attention and object use to engage with the AR system. This suggested that besides visuomotor skills required for object manipulation in the magic mirror view, other developmental symptoms can hinder children in the lower end of the autism spectrum to attend to and interact with the AR system. Since autistic children in this subgroup exhibit the most delayed development of symbolism, alternative AR approaches are yet to be explored.

Fifth, the current vehicle play themes are more appealing to boys and most of the participants signed up for the study were boys. Therefore the outcome of the study has a potential gender bias. More girl-friendly and mutual themed AR stimuli should be added and the effect with girls should be explored accordingly.

Lastly, this study focused on exploring the positive effect of AR in supporting symbolic play by comparing childrens play behaviours in the AR setting to an equivalent non-computer setting. Future studies are expected to obtain insight of the effectiveness of AR scaffoldings versus general novelty of computer technology in supporting symbolic play, by comparing children play behaviours in the AR setting to alternative non-AR technology settings such as virtual reality.

5.9 Conclusions

I presented the design and evaluation of an AR system to promote open-ended symbolic play for young children with ASC. Results indicate a positive effect of increased elicited symbolic play in frequency, duration and relevance when using the AR system as compared with a non-computer setup. Participants were highly engaged with the AR system and produced a diverse range of play ideas. Individual differences among participants predict a gradual effectiveness of the AR system for children in different autistic conditions, as results show that the AR system had the most effect for children with severe difficulty in symbolic play and the least for children with minimal difficulty. The AR system tends to have the most positive effect on children who have the most developmental delay in symbolic play. For children who have less impaired symbolic play, the salient visual effects of the AR system can be persuasive for them to adapt to new themes beyond their restricted interests. Moreover, I discussed skill transfer, usability and limitation of the AR system and summarized guidance for evaluating AR systems for children with ASC. I addressed the three research questions discussed early in this chapter through the exploration of applying psychology literature to the system and evaluation design, as well as the analysis of the evaluation results. I present major findings in response to each research question below.

For the AR system design, I explored the first level of the three-level AR approach as the underlying structure for solitary symbolic play enhancement, and integrated vehicle-related play theme into this structure to increase motivation. The design showed incremental scaffolding for the three main aspects of symbolic play deficits: cognitive (AR illustration for symbolic thought), executive (open-ended elicitation), and motivation (apply restricted interests to play themes). While the first aspect is tied with symbolic play, the latter two can be applied to the design for further play-based computer systems for children with ASC.

For the AR magic mirror usability, I observed how usable the AR system is in supporting different types of object manipulation with physical play materials. I found that autistic children with fine motor difficulties as young as four years old can manipulate physical play materials to carry out symbolic play ideas under the magic mirror view. This shows that children can learn to adapt visuomotor skills to the magic mirror coordinate system within a short period of time. It is also worth noticing that they intermittently switched to the world coordinate system for spatial relationship information between objects during relational manipulation, which reflects slight perceptual disorientation with inward/outward movements under the mirror view.

For the AR evaluation, I illustrated a rigorous approach to adopt existing experiment methods and developmental symptoms of children with ASC to the effectiveness evaluation of the AR system. This leads to a summary of considerations when designing evaluation for children with ASC and similar pervasive developmental symptoms based on the heterogeneous impairments with autism.

In the next chapter, I will continue exploring research questions in terms of design, usability and evaluation in the context of social symbolic play, which has drawn developmental psychologists' attention beyond autism to typically developing child groups. I will exploit the rest of the three-level AR approach to enhance social symbolic play, investigate usability of the magic mirror display in supporting the group user scenario, and extend evaluation methods to more complex social symbolic play behaviours.

Chapter 6

FingAR Puppet: Promoting Social Symbolic Play for Young Children

6.1 Introduction

The study in the previous chapter confirmed the positive effects of using AR technologies to enhance symbolic thought and divergent thinking in solitary symbolic play for young children with ASC. In this chapter, I continue investigating the potential of AR in promoting social symbolic play when symbolic thoughts are tightly integrated with social understandings and are collaboratively constructed among multiple players. These cognitive and social advances in social symbolic play directly contribute to the development of theory of mind, which is an important social cognitive ability to reason about mental states such as belief, desire, emotion, as well as pretense of self and other people. In Chapter 2, I elaborated on the importance of social symbolic play, individual differences among typically developing and autistic children, and a lack of emphasis on theory of mind development in conventional social symbolic play intervention. Since social symbolic play elicited in an AR environment involves more complicated human-computer and social interactions than in solitary symbolic play, in this study I focus on the initial exploration of the potential of AR to support social symbolic play for typically developing children. Findings from this study are expected to inform the design of future AR systems that encourage cognitive and social development for children with ASC, who encounter difficulty or developmental delay in social understanding and interaction.

In Chapter 3, I described how symbolic thought lies at the centre of socio-cognitive processes involved in social symbolic play. First, symbolic thought is the fundamental mental process that accommodates theory of mind development in symbolic play. The symbolic thought of attributing mental states to pretend roles as if they are independent agents encourages children to take perspectives of people distinct from themselves and predict their minds and actions (Hobson et al., 2009; Lillard, 1993a). Moreover, children begin to understand that people may hold different symbolic thoughts in their minds, thus they need to communicate symbolic thoughts with other players to establish and maintain joint pretense.

Second, symbolic thought is the core mental process that advances representational ability and stimulates divergent thinking. For children with ASC, difficulty in generating symbolic thought and associated play ideas are believed to be the two main causes for their impaired spontaneous symbolic play (see Section 2.2.2). The divergent thinking involved in the ideation processes of symbolic thought and play ideas is also considered an important creative process for typically developing children (Dansky, 1980b; Dansky and Silverman, 1973; Russ, 1993; Russ and Schafer, 2006).

In view of the key effects of symbolic thought on theory of mind and divergent thinking as discussed in Chapter 3, I am motivated to investigate AR design approaches to reinforce the latter two abilities by guiding appropriate symbolic thought conception. This process helps me to further explore the following research questions from a social perspective:

- What are key design considerations of AR systems that promote symbolic play for young children with and without ASC?
- How usable is the magic mirror display metaphor in supporting object manipulation in symbolic play?

First, this study places an emphasis on exploring the design space of AR to promote cognitive and social aspects of symbolic play. The previous study, as an initial proof of concept of using AR to support symbolic play, only examined the most fundamental elicitation method (level-1) of the three-level AR approach proposed in Chapter 3 to enhance solitary symbolic play by visually illustrating symbolic thought and encouraging divergent thinking on play ideas. This previous method, however, provided little support for children to conceive symbolic thought in an independent and divergent way, which is essential for more complex symbolic play. Focusing on social aspects of symbolic play, this study further exploits the rest of the three-level AR approach to enhance theory of mind and divergent thinking via reinforced support for symbolic thought.

Second, this study extends our knowledge about the usability of AR magic mirror to support collaborative play activities. The previous study showed that young children with fine motor difficulties can efficiently interact with physical objects under the AR magic mirror view. In a social symbolic play scenario, a child has to share such AR displays with other players. How efficiently they can manipulate physical objects with the shared AR magic mirror will be explored in this study. In addition, more complex interactions between the user and the AR system are introduced to support theory of mind and divergent thinking. Therefore related usability challenges are yet to be investigated. Both of these findings will contribute to the design of future AR systems.

In this study, I developed the FingAR Puppet system that aims to promote: (1) emotion expression and understanding; (2) verbal communication of joint pretense and (3) divergent thinking using open ended play materials. In the rest of this chapter I present the design, implementation and evaluation of the FingAR Puppet system, including an empirical study with 14 children aged 4 to 6. I found that children were highly engaged and carried out diverse social symbolic play episodes using the FingAR Puppet system. In particular, experiment results showed that the system effectively encouraged children to express and understand emotional states of pretend role, and they tended to make more explicit verbal communication about symbolic transformations using open-ended play materials. I discuss the theoretical implications of these findings, detailed usability issues of the shared AR magic mirror to support complex play activities and social interactions, as well as study limitations and future work.

The remainder of this chapter is structured as follows. In Section 6.2, I review related literature of theory of mind and divergent thinking in symbolic play, as well as existing computer systems that promote theory of mind development in play contexts. In Section 6.3, I describe the design of the FingAR Puppet system, followed by a description of the implementation in Section 6.4. In Section 6.5, I present a pilot study of the FingAR Puppet system and related improvements. In Section 6.6, I describe the design of the experiment to evaluate the effectiveness of the system in promoting social symbolic play and present the experiment results in Section 6.7. In Section 6.8, I discuss the main findings of the study, as well as study limitations and future work. In Section 6.9, I summarize the overall discoveries of this study and corresponding implications to each research question.

6.2 Related Work

Following the approach of using existing psychology literature to guide the design and evaluation of AR systems, I first review two fundamental elements of theory of mind in symbolic play: mental states and joint pretense. This leads to the integral design goal of the FingAR Puppet and provides an important reference for corresponding evaluation methods. I then review divergent thinking in symbolic play to obtain further design guidance for the FingAR Puppet system. Last, I review existing computer systems relating to theory of mind in play contexts, which confirms the contribution of the research goal pertaining to using AR to promote social symbolic play for young children.

6.2.1 Theory of Mind and Social Symbolic Play

Mental States and Social Symbolic Play

Emotion comprehension is one of the early forms of theory of mind that requires a child to understand that people's emotional reaction to the same situation differs according to personal desire or belief (Harris, 2000). There is a gradual development of emotion comprehension in early childhood. Research shows that children between 2-3 years old begin to relate one's emotions to obvious desires or goals. There is, however, a general lag between reasoning about belief on action (4-5 years old) and belief on emotion (5-6 years old) (Bradmetz and Schneider, 1999; Harris and Lipian, 1989; Rosnay and Harris, 2002). One well-studied example is that children are only capable of interpreting the emotion of surprise with false belief of story characters from around 7 years old (Hadwin and Perner, 1991; Ruffman and Keenan, 1996).

Many studies show that social symbolic play is closely related to emotion understanding (Nielsen and Dissanayake, 2000; Seja and Russ, 1999; Youngblade and Dunn, 1995). In spite of the connection between social symbolic play and emotion comprehension, there is a lack of research focus on reinforcing emotion expression and understanding from another person's point of view through modifying mental state in pretend roles in play.

In this study, I chose emotion as the initial target to explore potential effects of AR in promoting children's comprehension of other people's mental states in a social play context for three reasons: (1) emotion comprehension is one of the earliest forms of theory of mind ability; (2) emotion comprehension involved in social symbolic play requires children to actively reason about desire and belief of the pretend roles; and (3) emotion is associated with visual external cues, namely facial expression, which provide overt stimuli to encourage children to manipulate and communicate about.

Furthermore, I investigated measures for emotion comprehension in the psychology literature and identified two common measurements: occurrences of emotional state and causal elaboration. In a series of studies of autistic children's talk about psychological states, researchers measured the occurrence of emotion related behaviour including actions and utterances as well as causal elaborations when children mentioned cause or consequence relating to psychological states (Dunn et al., 1991; Tager-Flusberg, 1992; Tager-Flusberg and Sullivan, 1995; Youngblade and Dunn, 1995). They identified emotional state instances by the use of verbal emotion terms (e.g. happy, mad) and behaviour emotion terms (e.g. cry). They also labelled children explicitly mentioning the events causing the emotional state or the consequences. Moreover, Dunn et al. (1987) summarized a comprehensive corpus of gestural and verbal communication associated with emotional state and related causal utterance, as part of the investigation of young children's theory of mind development. The above literature provides sufficient reference points to develop measurements and corresponding coding schemes in this study.

Joint Pretense and Metacommunication

The notion that other people hold different pretense ideas only occurs to children during their preschool years as their theory of mind ability gradually matures (Ganea et al., 2004). This ability develops alongside joint pretense, which pertains to constructing shared symbolic thought among multiple players, so that play actions made by one player can be understood and responded to appropriately by others. Metacommunication is a special communicative technique to establish and maintain symbolic transformations of things, persons, actions and situations during joint pretense (Andresen, 2005; Garvey and Berndt, 1975; Goffman, 1974; Howes and Matheson, 1992). Metacommunication is defined as "communication about communication" (Ruesch and Bateson, 1951). In the context of social symbolic play, metacommunication refers to communication "functions to establish the play frame, to provide ongoing messages as to how behaviour should be interpreted, and to manage any alternation to this frame" (Whitebread and O'Sullivan, 2012). Garvey and Berndt (1975) studied the organization of symbolic play and proposed five forms of metacommunication: (1) negation of pretense; (2) enactment; (3) signals; (4) procedural or preparatory behaviours; (5) explicit mention of pretend transformations, such as role, object and plan.

Bateson et al. (1956) raised the concept of frame in play to differentiate between the contexts of "this is play" (within-frame) and "this is not play" (out-of-frame), and metacommunication resides both within and outside of the play frame. Giffin (1984) categorized metacommunication pertaining to symbolic transformation into seven types from "Enactment" which is totally within play frame to "Overt Proposals to Pretend" which is totally out of play frame. Alternatively, metacommunication is recognized as explicit and implicit (Sawyer, 1997). When the child speaks as a director or narrator (e.g. "pretend this (doll) is our baby"), it is regarded as explicit and usually occurs during planning or negotiating when there is conflict. When the child speaks as the character that he or she enacts, it is considered implicit which includes verbal (e.g. talks as the pretend character) or non-verbal (e.g. enacts the pretend character) strategies.

The above theory raises a special challenge for designing AR interfaces to elicit metacommunication from young children during joint pretense. Unlike symbolic play in a natural environment where one's symbolic thoughts are opaque to the playmates, in an AR environment the symbolic thoughts are externalized via visual illustration, thus accessible to all players simultaneously. In the case of explicit metacommunication of symbolic transformation, how to encourage children to verbally communicate symbolic thoughts besides gestural transformation (e.g. assigning a virtual police character to a generic physical puppet) is worth exploring in this study. In particular, based on the suggestion that vagueness of open-ended materials is helpful to promote the cognitive processes of conceiving and sharing pretense ideas (McLoyd, 1983; Trawick-Smith, 1990; Whitebread and O'Sullivan, 2012), I am motivated to explore the design space of using open-ended AR scaffolding of symbolic transformation to encourage corresponding metacommunication.

6.2.2 Divergent Thinking and Social Symbolic Play

Playfulness is suggested to be essential to promote divergent thinking, which is an important ideation ability that involves exploring one's knowledge and generating a variety of ideas (Christie and Johnsen, 1983; Guilford, 1968; Lieberman, 1977; Runco, 1991). It is one major cognitive process of creativity, which involves free association, broad memory scanning, and flexibility of thought (Runco and Pritzker, 1999). In particular, it is argued that freedom and fluidity of symbolic play lead to divergent use of play materials in response to make-believe themes (Dansky, 1980b; Dansky and Silverman, 1973; Russ and Grossman-McKee, 1990; Russ et al., 1999; Russ and Schafer, 2006; Singer, 1992).

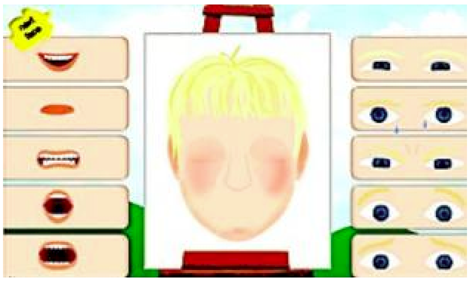
Previous research about the ideational processes suggests that individuals tend to create more fluent and original ideas when exposed to open-ended tasks (Guilford, 1968; Runco and Albert, 1985). Subjects tended to produce more divergent ideas when being stimulated to intentionally search for appropriate associations and responses (Runco, 1986a,b). Meanwhile, the divergent thinking process is also influenced by the characteristics of different stimuli (Moran III et al., 1983; Runco and Albert, 1985; Sawyers et al., 1983). It is argued that three-dimensional stimuli are more appropriate to promote divergent thinking than two-dimensional stimuli for preschool children (Moran III et al., 1983). Research also shows that the level of familiarity with divergent thinking tasks influences individuals' ideational responses in originality and fluency. For example, investigation shows that figural tasks can elicit more reliably original responses than verbal tasks due to lower familiarity of the former (Runco and Albert, 1985). Moreover, preschool children tend to produce a greater number of ideas with familiar tasks (Sawyers et al., 1983). These studies provide helpful empirical information to guide the design of the FingAR Puppet system. In particular, I am motivated to explore design approaches to elicit divergent thinking strategies during symbolic play through open-ended AR stimuli with a varied level of familiarity to children.

6.2.3 Computer Systems for Social Symbolic Play

The recently increasing use of computers in early childhood has drawn many psychologists' attention. In one investigation, Singer and Singer (2009) reviewed how imaginative play evolves with new digital media, and discussed possibilities for school readiness and imaginative enhancement using computers. In particular, they examined the relationship between VR games and symbolic play and advised that new computer mediated experiences have yet to be explored incorporating physical toys such as play figures, doll-houses, blocks and construction materials. Agreeing with Singer's view, I believe it is essential to break the cyberspace constraints and bring the rich representation and tangibility of physical objects into digitized symbolic play experiences, which are largely missing in VR-based imaginative games.

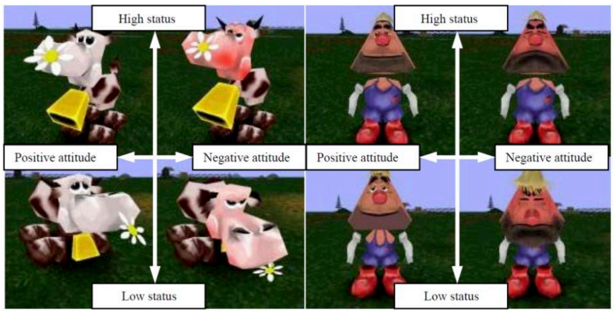
So far I am not aware of any computer systems that are especially designed to foster joint pretense and divergent thinking on symbolic transformation. This may be due to the lack of research of taking advantage of the dual representation feature of AR technologies to promote symbolic play as discussed in Section 2.3.1. There is also relatively little research on exploring computer-assisted social symbolic play to enhance emotion comprehension. Some studies focus on helping children to recognise simple emotions without relating them to social context. For example, Emotion Faces is designed to encourage preschool children to practice emotion recognition skills by matching face parts to show basic emotions (Humphries and McDonald, 2011). Other studies investigated enhancing emotion comprehension in a storytelling context. For example, with StoryFaces children can watch pre-made stories with virtual characters whose faces are replaced with the children's own faces, and make their own stories using these faces (Ryokai et al., 2012). Their empirical study shows that younger children aged four to five tend to only record happy and positive faces and do not particularly relate the facial expression with the story they make. One limitation of the StoryFaces system is that the static storytelling mode lacks support for improvisational and reciprocal social interaction, as promoted through role enactment in symbolic play. In addition, it mainly motivates children to reason about emotional states from their own perspective, instead of from others' perspectives.

Another example of facilitating emotion comprehension in digital play contexts is PUPPET, a VR environment with autonomous characters having different



(a) Emotion Faces (Humphries and McDonald, 2011)

(b) StoryFaces (Ryokai et al., 2012)



(c) PUPPET (Marshall et al., 2002)

Figure 6.1: Computer systems that promote emotion comprehension.

goals and emotional states (Marshall et al., 2002). The study shows that children aged seven to nine can sometimes understand characters' emotional states and interact with these characters appropriately to the narratives. The reseachers also suggested that being able to record childrens' dialogue is a promising method to promote reflective thought and improve dialogues in an iterative way. Similar to StoryFaces, PUPPET does not support reciprocal role enactment between multiple players. Another limitation is that children are restricted to pre-defined goals of virtual characters, which may not encourage extending emotion expression and response over time. In addition, the two-dimensional emotion space in the PUPPET system (status and attitude) is more subtle than discrete emotions (e.g. happy, angry), thus can be challenging for younger children to manipulate efficiently.

The above research shows the importance of relating emotion comprehension to social contexts involving different desires and beliefs of pretend characters.

(a) Enactment (b) Emotion switch (c) Open-ended scenery (d) Dramatic storyline

Figure 6.2: FingAR Puppet system overview.

Further research is yet needed in designing computer systems that enhance emotion comprehension, joint pretense and divergent thinking via social symbolic play. I address these research opportunities through the FingAR Puppet system in this study.

6.3 System Design

The design of the FingAR Puppet system had two goals. First, it was designed to provide a complete social symbolic play experience, including key elements of symbolic role, prop and scenery. Second, it aimed to enhance children's emotion expression and understanding, joint pretense and divergent thinking. Figure 6.2 shows the key features of the FingAR Puppet system, which include role enactment, symbolic transformation on emotional states, verbal communication on open-ended symbolic transformation, and creation of dramatic storylines.

I applied the AR magic mirror to support a reflected view of reality with imaginary objects and situations superimposed. The children look into this AR magic mirror while interacting with physical objects alongside other players in a tabletop play environment (Figure 6.3).

In the remainder of this section, I describe the core design concept of FingAR Puppet based on the three-level AR approach proposed in Chapter 3 (Section 6.3.1), and elaborate on the detailed design in terms of object transformation (Section 6.3.2), emotion transformation (Section 6.3.3) and system navigation (Section 6.3.4).

Figure 6.3: Children interact with the FingAR Puppet system.

6.3.1 Design Concept Overview

In this study, I exploited the design space of the level-2 and level-3 stimuli of the three-level AR approach proposed in Chapter 3 to enhance social symbolic play. As Figure 6.4 shows, the primary representation of reality in the FingAR Puppet system contained the following physical referents: finger puppets, blocks and generic shapes. The imaginary representations corresponding to each type of physical referent included the role, prop and scenery. The goal of each level of stimuli is presented below.

Level-2 stimuli aimed at promoting the formation of symbolic thought by providing children with a set of imaginary representations with definite-meanings. Symbolic transformations (e.g. "the puppet is a policeman" or "the block is a car") occurred when a child assigned an imaginary representation (e.g. a policeman or car) to a primary representation (e.g. a puppet or block). In particular, the system aimed to elicit the symbolic transformation of attributing emotional states to a pretend role by allowing the child to assign facial expressions (e.g. a scared face) to a pretend role. I chose facial expression as the key facilitator to encourage children reasoning and communicating about emotional states because of its salient visual properties as discussed in Section 6.2.1, as well as the research opportunity identified in Section 6.2.1 to support fluent affective enactment of pretend roles for young children in spontaneous social contexts. Supporting symbolic transformation of emotional states of pretend roles is a specific scenario of the fundamental proposal raised in Section 3.2.2 that AR can function as an external cognitive structure to enhance symbolic play through physical manipulation

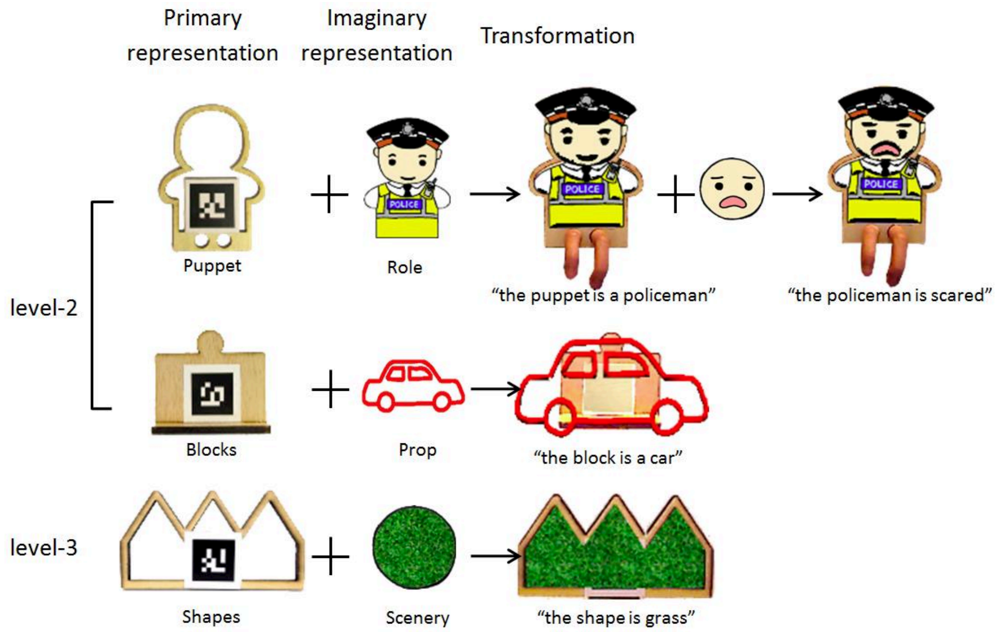


Figure 6.4: Overview of the FingAR Puppet design approach.

of the otherwise invisible imaginary representations. In particular, I hypothesize that enabling real-time facial expression manipulation of pretend roles can encourage children to express and reason about emotional states during symbolic play.

Level-3 stimuli aimed to further enhance the formation of symbolic thought in a more independent and divergent way by providing a set of imaginary representations with open-ended meanings. A child was required to conceive symbolic thoughts by extending the imaginary representation with their own symbolic interpretation in response to the play theme and plan. Based on findings that open-ended materials are helpful to promote conceiving and sharing pretense ideas (McLoyd, 1983; Trawick-Smith, 1990; Whitebread and O'Sullivan, 2012) and encourage divergent thinking (Guilford, 1968; Runco and Albert, 1985), I hypothesize that the ambiguity of symbolic thought constructed with open-ended imaginary representations encourages: (1) explicit metacommunication of object transformation to establish joint pretense; and (2) divergent thinking on possible imaginary representations.

Interaction with the system involves two phases: preparation and play. This

Figure 6.5: A collection of primary representations of the FingAR Puppet system.

follows the out-of-frame and within-frame play structure discussed in Section 6.2.1. During the preparation phase, children set up roles, props and scenes in order. Each child has one puppet, several blocks, and several shapes. First, children transform their puppets to the roles they want from a set of pre-defined social or fictional roles. Second, they transform blocks to props from a pre-defined set related to these roles. Finally, they create related scenes by assigning open-ended material properties to generic wood shapes. During the play phase, children were encouraged to make stories together using the AR elements they had chosen. During the play phase, children were also able to (1) change the facial expression of their puppets; (2) change role, prop or scenery whenever necessary; and (3) record a video of the play.

6.3.2 Object Transformation

The primary representations of the FingAR Puppet system were composed of a group of puppets, blocks and shapes made of plywood using a laser cutting machine (Figure 6.5). They are the physical referents of imaginary representations provided by the system.

The imaginary representations of the FingAR Puppet system were designed

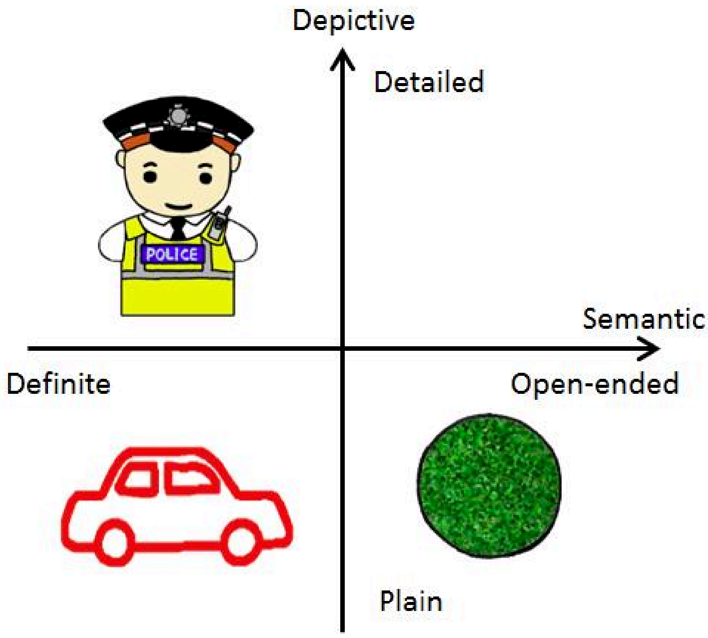


Figure 6.6: The representational correspondences used in AR stimulus.

with varied visual detail in order to evoke ideation of symbolic transformation with gradual cognitive efforts. Because mental representations constructed through visual perception can be analogous to either language or drawing (Pitt, 2013), the AR materials in our system were designed to carry representational correspondences in two dimensions: semantic and depictive (Figure 6.6).

First, in the semantic correspondence dimension, I designed roles and props with definite meaning, and scenes with open-ended meaning. The design was intended to require different degrees of mental efforts to decide the physical referent and target for object transformation. For roles and props, children only had to choose from a selection of virtual objects with definite meanings as the transformation target. The simplicity ensured that children focused on the development of core elements of a play theme. For scenes, the system deliberately left a cognitive space between the physical referent and the target object for transformation to promote divergent thinking. Children had to create their own meaning of the target object for transformation by proactively assigning open-ended materials to a specific physical shape. The transformation result was expected to be less obvious than those with definite meanings in the role and prop selection periods. Therefore, I hypothesized that in the scenery selection period, children tended to assure both themselves and their playmates about the transformation they made by verbally clarifying the meaning associated with the physical referent.

Second, there was a different level of detail for the depictive rendering of virtual objects. I depicted the roles in a detailed visual form in order to provide overt occupational and fictional properties, which were essential to support the ideation of play themes. The vivid visualization of roles was designed to motivate children to carry out more role-directed play episodes as well as identify different facial expressions. In contrast, I designed props in a plainer abstract form to make them semantically unambiguous but visually simple. The design intention was to provide props with enough cues to support role and theme related play, but less visually appealing to children in order to assure optimal role-directed play. Last, I designed scenes as abstract materials to encourage children to create their own symbolic interpretations by combining scenery materials with physical shapes.

Role

I chose to base the FingAR Puppet concept on the finger-leg puppet, a familiar and cheap toy for young children. Traditional finger leg puppets are made by drawing figures on paper and cutting two holes at the bottom. Finger leg puppets are more agile and expressive than dolls, and easier to operate than other forms of puppet such as glove puppets, marionettes and shadow puppets. In addition, like other forms of puppet, the finger-leg puppet requires a child to hold the puppet throughout the play, which encourages role playing and thus increases the chance for theory of mind practice. The simplicity is essential to guide children's focus from simulating realistic body movement of the puppet to using the puppet as an expressive anchor to collaboratively carry out social play ideas with the playmates.

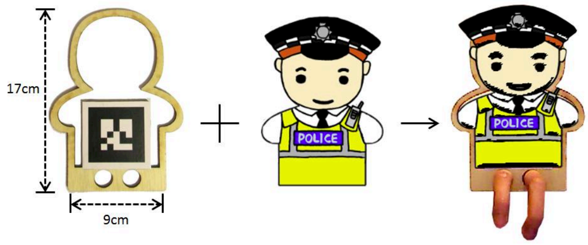
A child held the generic finger puppet by putting their index and middle fingers through the holes on the bottom of the puppet. He or she could then transform the generic puppet to a specific role by associating a virtual role with it (Figure 6.7(a)). The physical referent of the FingAR Puppet inherited the simplicity of operation from a traditional finger leg puppet while the virtual role representation in particular enabled the child to explore emotion aspects of role-play, which are usually unavailable in a traditional puppet play experience.

Children were able to select from 18 social and fictional based roles, all sharing the same pose and facial features (Figure 6.7(b)). Based on common play themes of children's social symbolic play (Burns and Brainerd, 1979; Garvey and Berndt, 1975; Sawyer, 2003), the system supported several role-specific play themes such as rescue (e.g. policeman and fireman), restaurant (e.g. chef and waiter), shopping (e.g. shopkeeper), hospital (e.g. doctor, nurse), and adventure (e.g. princess, knight, pirate). Research shows that children tend to enact roles of their gender (Fein, 1981). I therefore kept a balanced number of male and female roles to ensure that they were attractive to both girls and boys. The default facial expression of all roles was composed of a weakly smiling mouth, with eyes and eyebrows in a neutral position. Research shows that a weak smile is preferred as a neutral face than the straight-line mouth, as the latter makes some children think of anger (Read, 2008).

Prop

I provided wood blocks in a generic rectangular shape as the physical referent for props (Figure 6.8(a)). The grip on top of the block was meant for the child to hold when selecting and moving the prop, in order to prevent marker occlusion. As mentioned earlier, children find it easier to substitute physical referents to pretense objects when they share a similar shape and the former one provides a general function (Jackowitz and Watson, 1980). Therefore, I designed the rectangle blocks with both vertical and horizontal orientations to suit the orientation of the virtual props.

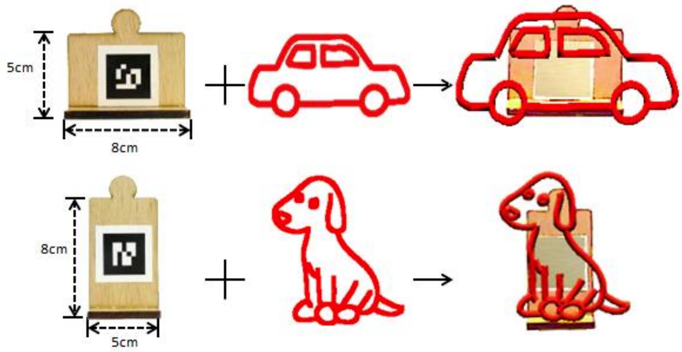
There were 12 virtual objects as the target for prop transformation (Figure 6.8(b)). They were rendered in a 3D wireframe style and related to the specific themes of the pre-defined roles, such as fire engine with the rescue theme, cake with the dining theme, dragon with the adventure theme, etc. The visual representations were illustrative meaning-wise, so that children had to rely on the semantic of the props during the play and conquer the nonfactual aspects of the abstract representation (e.g. all props looked red, a dog was of similar size to a car, etc.). The child could flip the orientation of the prop by flipping the associated wood block. An extended reason for the wireframe style visual representation was that it was easy for young children to make similar line-based



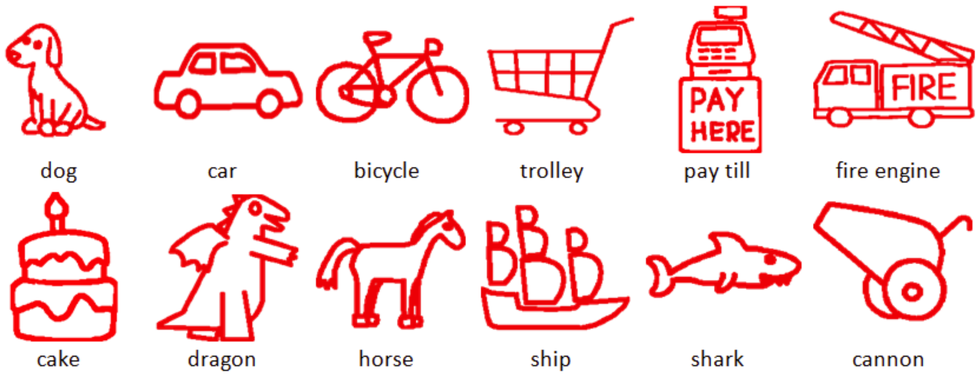
(a) Role transformation

(b) Imaginary representations of roles

Figure 6.7: Symbolic transformation of roles.



(a) Prop transformation



(b) Imaginary representations of props

Figure 6.8: Symbolic transformation of props.

drawings. I intended that in the future, users will be able to draw their own target props while maintaining visual consistency with the existing props.

Scenery

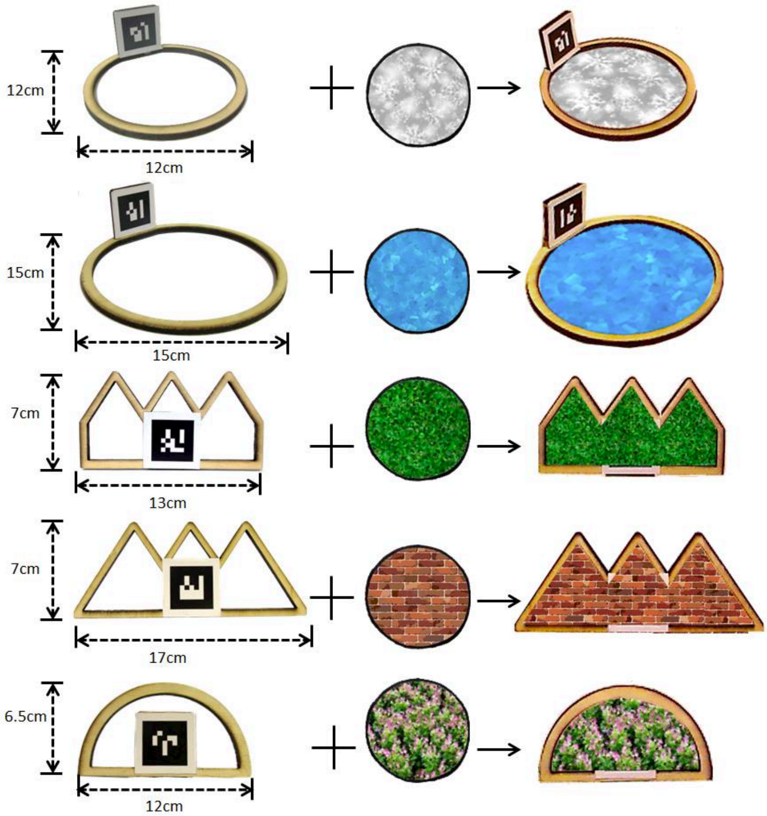
There were three types of wood shape in the scenery selection period: circle, semi-circle and sawtooth. I provided two types of circle and sawtooth with slight variations in size and shape to avoid possession conflicts between players. Examples of combinations of shape and material are shown in Figure 6.9(a). There is a grip at the back of each shape for the user to hold when choosing a material (Figure 6.9(b)).

I chose 12 materials to help children create meanings for physical referents (Figure 6.9(c)). Some materials reflected natural scenes (e.g. flower, grass, water, snow, wood and stone) or built environment scenes (e.g. brick, tile and fire). The rest of them were of more ambiguous meaning.

As discussed in Section 6.2.2, previous research suggests that one's level of familiarity with different stimuli affects divergent thinking processes in terms of fluency and originality (Runco and Albert, 1985; Sawyers et al., 1983). Based on this theory, I designed scenery materials with different degrees of familiarity to children in order to encourage them to (1) create different pretense interpretations with familiar materials; and (2) create more novel pretense interpretations with unfamiliar materials.

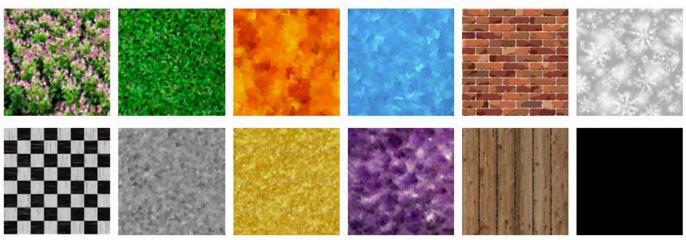
Interaction for Object Transformation

To complete the object transformation, the child pointed a physical referent at a target role, prop or scenery as if they were displayed on a mirror. The corresponding virtual object was then attached to or combined with the physical referent (Figure 6.10). In the role and prop selection period, one virtual object can only be chosen once. The goal of this design was to enhance the level of social sharing between users to help maintain group focus and awareness (Scott et al., 2003). In the scenery period, a material could be chosen more than once in order to encourage divergent thinking by combining one material with different physical referents to conceive different imaginary representations.



(a) Scenery transformation

(b) The design of the grip for scenery shapes



(c) Imaginary representations of scenery

Figure 6.9: Symbolic transformation of scenes.

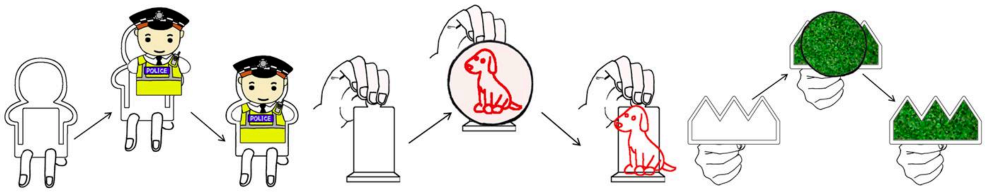


Figure 6.10: The illustration of interaction for object transformation. From left to right: transformation for roles, props, and scenery.

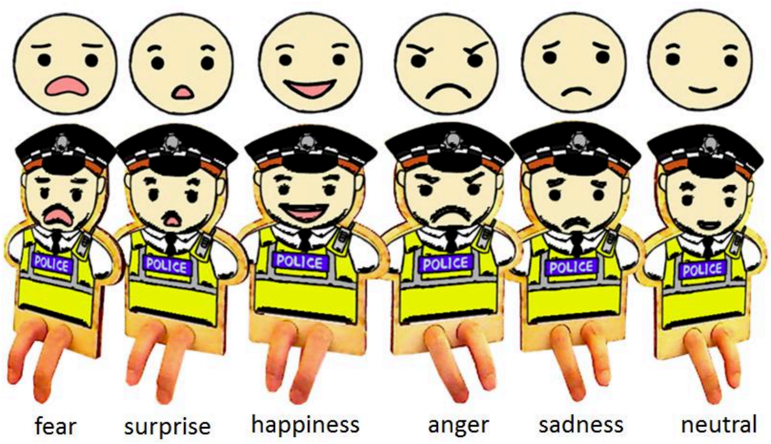


Figure 6.11: The collection of facial expressions.

6.3.3 Emotion Transformation

In this section, I first present the visual form of facial expressions of the puppet. I then describe the design of interaction methods to switch between facial expressions by comparing three different design solutions.

Facial Expression Visual Form

I designed six facial expressions (fear, surprise, happiness, anger, sadness, and disgust) based on the basic emotions set proposed by Ekman (1992) in addition to the neutral facial expression. I excluded disgust from the original facial expression set to simplify the selection choice because previous research showed that disgust is least recognizable by young children among the six basic emotions (Camras and Allison, 1985). The corresponding visual effects applied on a virtual role are illustrated in Figure 6.11.

(a) Swipe starts (b) Swipe ends (c) Change to the next facial expression

Figure 6.12: Action flow of swipe-based emotion switch.

Facial Expression Switch

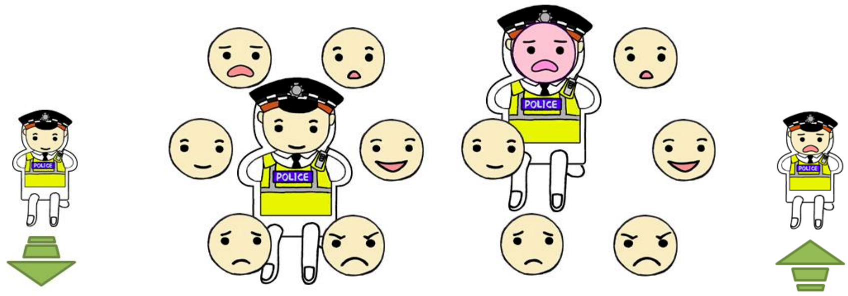
I explored and implemented three different interaction methods during the interaction design for facial expression switching. I describe the design of each method in this section and compare them in terms of ease of access to and efficiency to change facial expression.

Swipe-based Switch

The idea of swipe-based switching was to enable the user to change the facial expression of the puppet in a loop manner. A concept illustration is shown in Figure 6.12. The user held the puppet with one hand and used the other hand to swipe on the physical referent to switch the facial expression. The advantages of the swipe-based switch were that the gesture was simple and the user's finger received tactile feedback against the physical referent when swiping. The main disadvantage of the swipe-based switch is that the average number of gestures to reach the target facial expression was high and available facial expressions were not visible.

Single-handed Switch

The single-handed switch was designed considering the limited bimanual manipulation capability of young children. As illustrated in Figure 6.13, when the user moved the puppet close to the screen, a facial expression dial was triggered around the puppet. The user moved the puppet to point at the target facial expression. The user withdrew the puppet to dismiss the dial. The advantages of this design included: (1) the user saw all facial expressions at the same time; (2) the user could choose the target facial expression with one action; and (3)



(a) Move towards screen

(b) Trigger expression

(c) Choose expression

(d) Move away from the screen

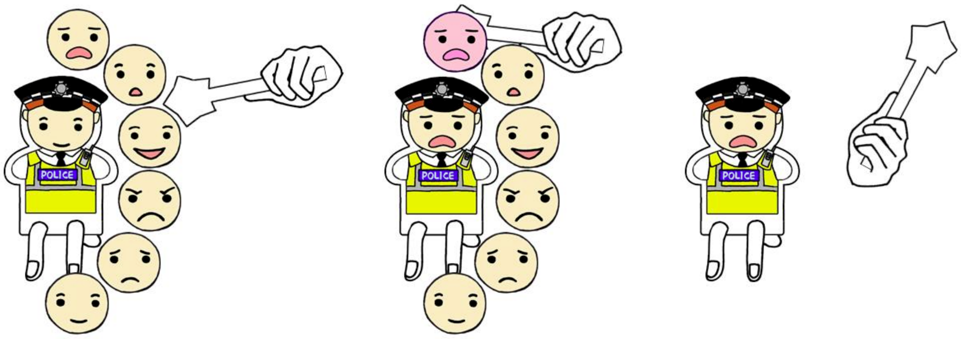
Figure 6.13: Action flow of single-handed emotion switch.

it only involved one hand. The disadvantages included: (1) it was unnatural for the user to keep their arm reaching out in order to trigger and choose from the facial expression dial; and (2) the pointing precision dropped when reaching out the arm.

Wand-based Switch

With the wand-based switch method, the user moved a physical wand towards the puppet to trigger the facial expressions and pointed the wand at the target facial expression to switch (Figure 6.14). The user moved the wand away from the puppet to dismiss the facial expressions. The advantages of the wand-based switch included: (1) the user saw all facial expressions at the same time; (2) the user could choose the target facial expression with one action; and (3) the user was able to change the facial expression of the playmate's puppet. The last advantage provided a unique inter-subject interaction scenario pertaining to emotion expression and understanding. When a child changed the facial expression of the playmate's character, the playmate had the opportunity to reason and respond to the unexpected emotional state change. The main impediment to the wand-based switch was the requirement of a certain level of bimanual manipulation skills.

There are two usability considerations for the facial expression-switching feature: ease of access to and efficiency to change facial expressions. First, it should be easy to access as the children already had several play objects to manipulate. If triggering the facial expressions required too much effort, they might not be motivated to explore this feature often. Second, the facial expression switching should be quick. Once the children started with the enactment, minimal inter-



(a) Trigger expression (b) Choose expression (c) Dismiss expression

Figure 6.14: Action flow of wand-based emotion switch.

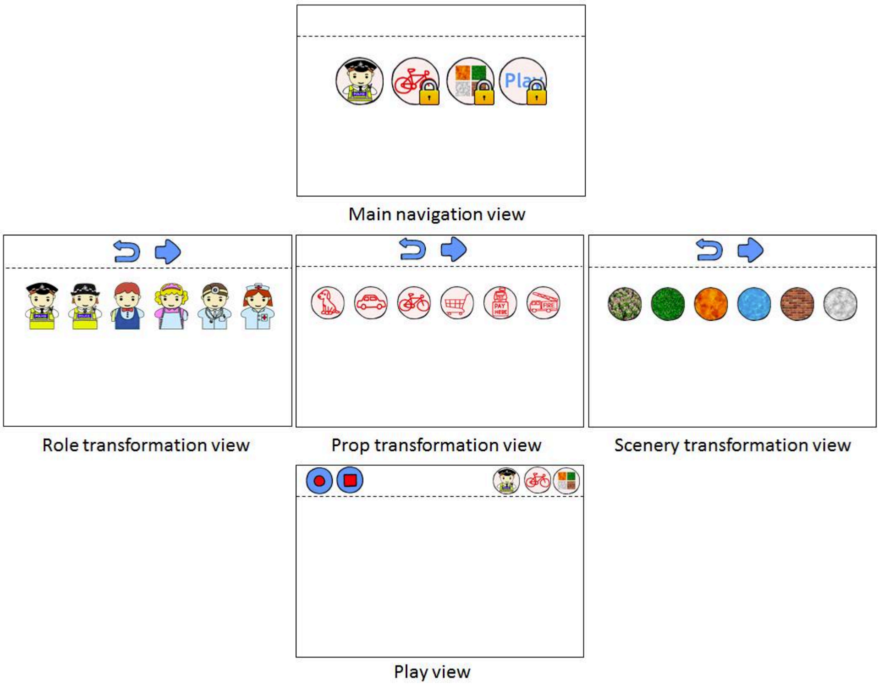
ruption was expected in order to keep a smooth flow of the storyline. Bearing these two goals in mind, the wand-based method provided a trade-off solution to ensure both accessibility and speed of facial expression switching, while the swipe-based method took too long to complete on average and the single-handed method was not as convenient as the other methods to get access to the facial expressions.

6.3.4 System Navigation

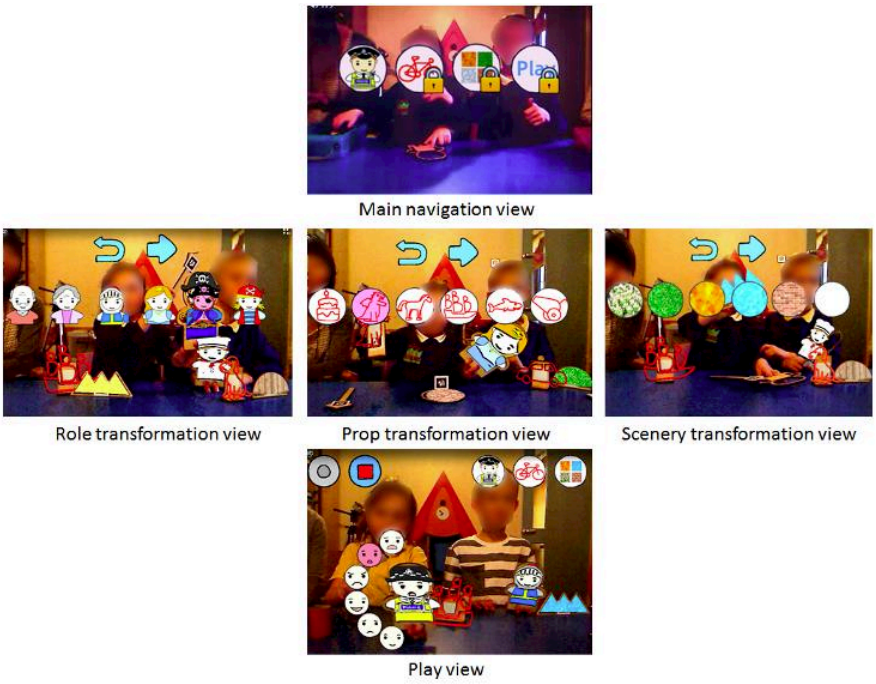
There were three types of views that the user navigated with the FingAR Puppet system (Figure 6.15): (1) main navigation view; (2) transformation view (role, prop and scenery); and (3) play view. There were two function areas that remained consistent across these views. The main area provided the space for the main interactions of each view while the upper area hosted secondary interactions.

Main Navigation View

The system began with the navigation view. It was designed to guide the users to prepare roles, props and scenes in a sequence. For example, they could only enter the prop view after they had visited the role view. A padlock symbol was displayed on the bottom right of the locked items. All of the four items were animated to slowly vibrate around a fixed center, as a visual effect to attract the users' attention. When the user used the magic wand to point at an item, a



(a) Illustration of the system navigation



(b) The actual user interface

Figure 6.15: System navigation.

progress loop appeared. If within one second the wand was still pointing at the same item, the system navigated to the corresponding transformation view.

Object Transformation Views

The role, prop and scenery transformation views shared the same layout. In the main area, six target items were laid in a horizontal row with the same slow vibration animation as items in the navigation view. The user used related physical referents to choose from these target items. The horizontal row was designed to ensure a reasonable number of target objects per view and to allow enough space to perceive the transformation effect. To see more items, the user used the magic wand to point at the "next" arrow (right) in the upper area. To go back to the main navigation view, the user pointed the magic wand at the back arrow (left).

Play View

In the play view, the user carried out the story in the main areas. To start recording, the user pointed the wand at the first button on the left side of the upper area. To stop the recording, the user pointed the wand at the second button next to the recording button. To enter the transformation view to change role, prop or scenery, the user pointed the wand at one of the three buttons on the right side of the upper area.

6.4 System Implementation

I developed the FingAR Puppet system based on a similar module infrastructure to the system developed in Chapter 5. It was built on several open source libraries including Microsoft XNA Game Studio 4.0 (system framework) (Microsoft, 2010), GoblinXNA 4.1 (AR registration and rendering) (Oda, 2011), ALVAR2.0 (marker tracking) (VTT, 2011) and Emgu CV2.4 (image processing) (canming, 2012). In the following sections, I describe the detailed implementation of the system.

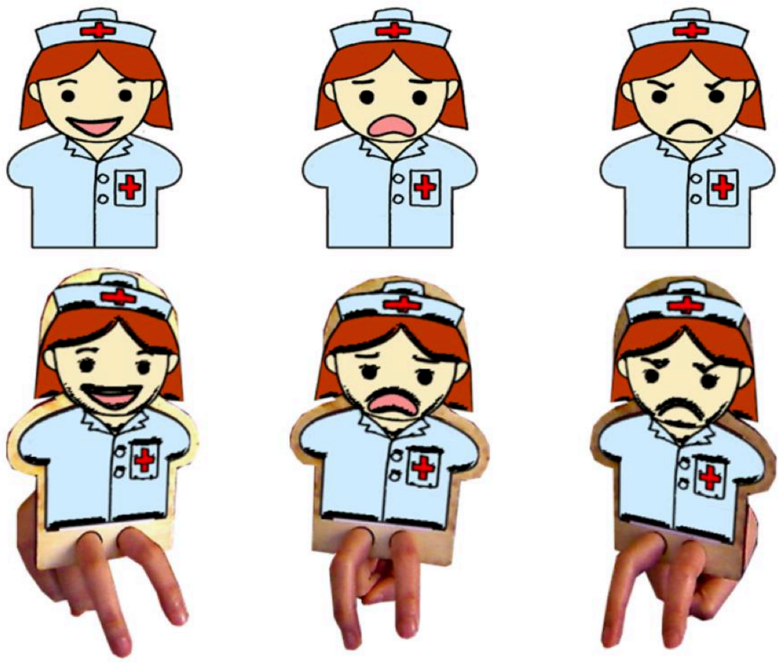


Figure 6.16: Illustration of facial expression enhancement of 3D models compared to 2D images.

Role

As described in the design section, I identified the vividness of the visual illustration of roles as a critical element to capture children's attention for role-directed play and facial expression recognition. In this section, I describe the pipeline I made to create 3D models from 2D images of roles. I created the 3D models from 2D images because: (1) a 2D image is easy to generate and it potentially enables user authoring in the future; and (2) the shadow details produced by the 3D model enrich the visual illustration of the role and facial expression, as Figure 6.16 illustrates.

I implemented a "rise up" 3D effect similar to baking cookies which involved three major steps (Figure 6.17): (1) generate a distance transform image (Rosenfeld and Pfaltz, 1966) of the original 2D image; (2) create a 3D mesh model based on the distance transform image; (3) map the original image as texture to the 3D mesh.

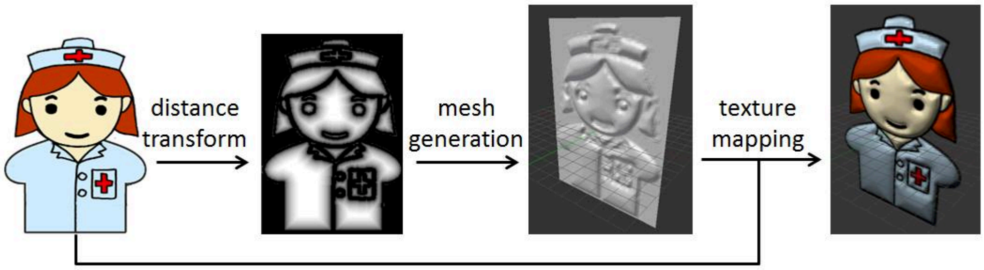
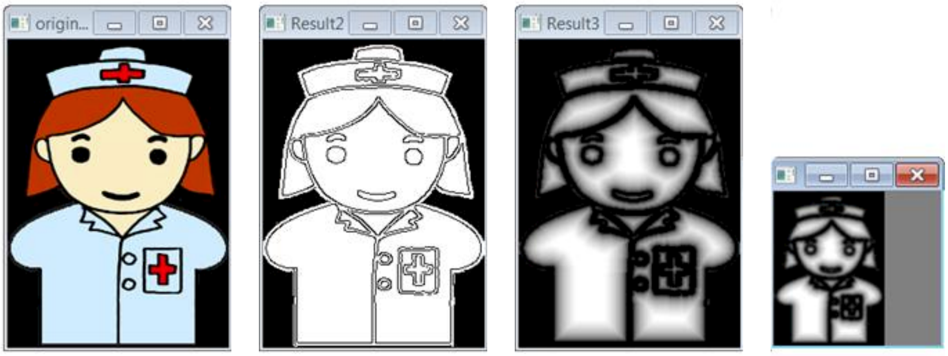


Figure 6.17: Implementation pipeline of the “rise up” 3D effect.



(a) Original image (b) Edge detection (c) Distance transform (d) Scale down

Figure 6.18: Procedures to produce the distance transform image.

Using the distance transform method, the system calculated the smallest Euclidean distance from each pixel to the surrounding edges as its Z value. In brief, the further the pixel was to the nearest edge, the bigger the Z value would be. The detailed procedure is shown is Figure 6.18, which included four steps: (1) read the original image; (2) use the Canny edge detection algorithm (Canny, 1986) to extract edges; (3) generate a distance map image using a distance transform and Gaussian smoothing algorithm; and (4) reduce image size by two to control the processing time and the size of the final mesh file.

The next step was to generate polygon meshes based on the distance map image. I used the Object File Format (.off) (Object File Format, 2014) to store the description of the polygon mesh information of the 3D object. The information included in the .off file was: (1) number of vertices, faces and edges; (2) list of vertices: X, Y and Z; (3) list of faces: number of vertices followed by a sequence

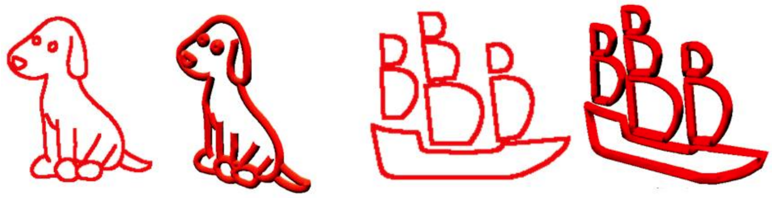


Figure 6.19: Constructing wireframe style 3D props from 2D images.

index of the composing vertices. In the conversion, each pixel was considered as a vertex and three adjoining vertices to construct one triangle mesh face. After the .off files were generated, the role model loader of the program read the .off files and constructed corresponding 3D models compatible to the GoblinXNA library. The model loader then mapped the original image as texture onto the 3D model.

Facial Expression Switch

I first created 2D images for each role with a blank face and a separate set of facial expressions. For each role, I mapped different facial expressions onto it, and converted the 2D images of each role with different facial expressions into separate 3D models. When the user interacted with the system to change facial expression, the system simply switched to a 3D model of the same role with a different facial expression. The same mechanism can be applied in an automatic pipeline in the future to enable the user to create new roles and facial expressions.

Prop

I constructed 3D wireframe models based on 2D images (Figure 6.19) using Blender 2.6 (Blender.org, 2012), a free 3D modelling software. The procedure included: (1) import the 2D image in .svg format and the stroke in 2D is recognized as a curve; (2) set geometric properties (bevel and extrude) of the curve to make it pipe-like; (3) convert the curve to a mesh; and (4) export as .fbx file, which is recognisable by the Goblin XNA library.

Scenery

The scenery was designed in a way that for each physical shape, there was a predefined virtual shape associated with it. The virtual shapes are initially invisible.

(a) Experiment apparatus (b) Participants interacting with the system

Figure 6.20: Pilot study in the usability lab.

When the user points the physical shape at a scenery material, the material is then assigned as the texture of the virtual shape.

Recording

When the user started recording, the program invoked a command line interpreter provided by Camtasia Studio software (TechSmith, 2005) to capture the screen of the FingAR Puppet system as well as the audio input. The video was recorded at 3 frames per second in order to reduce the size of the output file. Since a separate program hosted the recording, it assured optimal run-time performance of the FingAR Puppet system.

6.5 Pilot Study and Improvements

I conducted an initial pilot study with three pairs of typically developing children aged three to five in the usability lab of the Computer Laboratory in the University of Cambridge (Figure 6.20). There was one boy and one girl in each pair, and only one pair of participants knew each other before the pilot study. They were recruited through colleagues in the Computer Laboratory. The purpose of the pilot study was to identify usability issues of the FingAR Puppet system and evaluate the experiment procedure for the formal study in schools.

Participants in the 3-year old pair could carry out basic selection interaction with roles, props and scenery, however their aim was usually poor and they frequently held the body of the physical referent instead of the grip, which caused intermittent marker occlusion. In particular, the boy had difficulty with the point-and-choose concept. He kept leaning forward and trying to point the physical referent at the screen in front of him, instead of watching himself moving the physical referent in the AR magic mirror. For facial expression switching, they understood the concept but lacked fine visuomotor skills to change face efficiently. Most of the time they changed the face randomly by waving the wand close to the puppet. Overall they understood the interaction concept of the FingAR Puppet system, but had difficulty interacting with the system due to less developed visuomotor abilities.

Participants in the 4-year old pair were better at selection interaction due to better aiming skills and they learnt to hold the grip to avoid marker occlusion under my explanation. The participants learned to use the wand to change facial expression but their aim was less precise. They seldom changed the puppet facial expression during the play session, and they relied on my help to lead them through the navigation views for the preparation phase. As with the 3-year old pair, the participants needed parents' prompts to create simple storylines and there was little verbal interaction between the two players through either negotiation or pretend role enactment.

Participants in the 4 and 5 year old pair who knew each other were the most competent to interact with the FingAR Puppet system. They were able to select, navigate and switch facial expressions with the system with minimal adult guidance, and independently created simple story plots. Social interactions included enacting roles to talk with each other and discussing during the preparation phase. The performance of this pair indicates the visuomotor readiness of children above 4 years old and the importance of familiarity between players to be actively engaged in social interaction during play. These observation also shows that the bimanual manipulation involved in facial expression switching required much more effort for children to complete compared to simple selection actions.

Based on findings in the above pilot study, I made the following improvements and experiment decisions. Major usability improvements included: (1) enlarging the effect area of selection items to enable selection with less precise aiming; and (2) adding new props and scenes to enrich object transformation. Major experiment decisions include: (1) setting the age group for the formal evaluation as 4-6 years old to ensure the readiness of participant's visuomotor abilities; and

(2) recruiting participants in pairs according to familiarity.

I also demonstrated the system to researchers in developmental psychology, education and HCI and received much positive feedback, especially on the facial expression switching and recording features. I also visited three local nursery and primary schools when recruiting for the formal experiment. Teachers' feedback further confirmed my design decision for the FingAR Puppet system and two of them mentioned that simultaneously holding the puppet and selecting with the wand might be difficult for children below 4 years old, which was consistent with observations in the pilot study.

6.6 Experiment Design

I designed a within-subjects experiment to evaluate the effectiveness of the FingAR Puppet system in promoting emotion expression and understanding, metacommunication of joint pretense and divergent thinking. There are three null and alternative hypotheses:

- $\mathbf{H}_{0A}$: There is no significant difference in the frequency of the occurrence of emotional state during play between the facial expression switching disabled and enabled conditions.

  $\mathbf{H}_{1A}$: Enabling facial expression switching can encourage participants to express emotion more frequently during play.

- $\mathbf{H}_{0B}$: There is no significant difference in the frequency of causal elaboration of emotional state during play between facial expression switching disabled and enabled conditions.

  $\mathbf{H}_{1B}$: Enabling facial expression switching can encourage participants to reason about emotion more frequently during play.

- $\mathbf{H}_{0C}$: There is no significant difference in the percentage of explicit verbal communication per object transformation between scenery selection period and role and prop selection periods.

  $\mathbf{H}_{1C}$: The open-ended scenery transformation can encourage participants to explicitly communicate about joint pretense.

In the experiment, each pair of participants interacted with the FingAR Puppet system in two conditions: facial expression switching disabled (Face_Switch_OFF) and enabled (Face_Switch_ON). The order of the two conditions was counterbalanced in order to eliminate learning and novelty effects. In both conditions participants were asked to make stories with the system for 15 minutes. The sessions for each condition took place on a separate day.

6.6.1 Participants

Fourteen participants, eight girls and six boys from 48 to 74 months ($Mean$ = 63.00, SD = 8.79), were recruited from a local primary school. All parents of the participants signed a consent form and provided basic information about their child on a parent questionnaire (see Appendix C.1 and C.2). Each participant received a thank you certificate at the end of the study as a reward. Teachers paired participants into seven groups based on their familiarity with each other (three mixed-gender groups, two girl-only groups and one boy-only group). Twelve of the participants had at least one sibling. Eleven participants used computer devices at least once a week and the others on a daily basis. The types of software applications that they use include gaming, education, storytelling and music. The verbal mental age of participants was from 58 to 77 months ($Mean$ = 67.14, SD = 7.23) based on the British Picture Vocabulary Scale, 3rd edition (BPVS3) (Dunn and Dunn, 2009).

6.6.2 Apparatus

The study took place in a common room between the nursery and reception classes during normal school hours. The setup of the AR system included: (1) a Macintosh Laptop; (2) a 24-inch monitor; (3) a Logitech Webcam Pro 9000; (4) a 55*110*50cm table and (5) play materials (Figure 6.21(a)).

6.6.3 Procedure

I conducted the experiment on three consecutive days with the support of three teaching assistants. On the first day, I taught all participants, one group at a time, how to use the AR system. I then let the participants explore the system freely for about 10 minutes. On the second day, the participants were asked to carry out

(a) Interaction area (b) Recording area

Figure 6.21: The experiment apparatus.

play in pairs for 15 minutes in either the Face_Switch_OFF or Face_Switch_ON condition. At the beginning of each session, I gave identical instructions: “You are going to make a story together and you can play for 15 minutes.” During each session, the teacher and I provided minimal prompts only when the participants were obviously not engaged in the play or had difficulty developing play ideas independently. After 15 minutes, I waited for the current play episode to finish and asked the participants to stop. I then went through the child questionnaire with each participant. The procedure was repeated on the third day, except the condition was switched for each group. At the end of the two sessions, I had the teaching assistants fill out a teacher questionnaire and conducted a structured interview.

6.6.4 Data Collection

I used a video camera to record the participants’ play behaviours during each session of the experiment (Figure 6.21(b)). I used the video footage as the source for transcription, edited using Camtasia Studio software. I transcribed video footage of day two and day three into discrete metacommunication occurrences, including all individual actions and speech.

I conducted interviews with both participants and teaching assistants in the experiment. The child questionnaire included how they enjoyed playing with the

AR system, things they liked and disliked about the system and their preference between the two conditions. The teacher questionnaire included ratings for participants' engagement, theme appropriateness, participants' performance, and potential effectiveness of the system in promoting social symbolic play. This was followed by a structured interview to further discuss each aspect mentioned above. Blank teacher and child questionnaires are included in Appendix C.3 and C.4.

6.6.5 Measurements

I adopted several measures from existing literature in early childhood development reviewed in Section 6.2.1 to design the coding scheme for emotional state, causal elaboration and metacommunication on object transformation (Dunn et al., 1991; Garvey and Berndt, 1975; Giffin, 1984; Sawyer, 1997; Tager-Flusberg, 1992; Tager-Flusberg and Sullivan, 1995; Youngblade and Dunn, 1995).

Emotional State

Indicators of emotional states include: (1) verbal emotion terms (e.g. happy, sad, angry, etc.); (2) behavioural emotion terms (e.g. cry, kiss, hug, etc.); and (3) tone of voice (e.g. angry voice). I counted the total number of verbal and gestural emotional states that occurred within the metacommunication occurrences of each participant. If the same emotional state occurred more than once in the same metacommunication occurrence, it was only counted once. If there was more than one different emotional state in the same occurrence, each one was counted independently. I then divided the total number by the play time (minute) of each group in both conditions to calculate the frequency of emotional state occurrence. In order to make a rigid comparison between the two conditions, I excluded the facial expression switching action in the Face_Switch_ON condition from counting as emotional state occurrences. I made the initial coding and then randomly selected a 4-minute clip from each video (23% of the total video footage) for inter-subject reliability evaluation. An independent rater who was unaware of the hypotheses was invited to code the emotional state occurrence with the subset of video clips and the inter-subject agreement was highly satisfactory (Cohen's kappa = 0.98).

Causal Elaboration of Emotion

Causal elaboration was identified as a pair of verbal or gestural metacommunications that revealed the cause and effect relationship of certain emotional states. Within the pair, at least one of the metacommunication occurrences contains emotional state. For example:

(1) Child A said: "I'm *angry* now" [effect]
Child B said: "because there are no customers" [cause]

(2) Child A said to child B: "happy birthday" [cause]
Child B made his puppet *kiss* child A's puppet and said: "thank you" [effect]

The causal elaboration could also be within one metacommunication occurrence. For example:

(1) Child A said "I'm *sad* [effect] because my dog went missing [cause]"

For each metacommunication occurrence containing emotional state, I (1) checked if there was any causal elaboration within this occurrence; and (2) checked all metacommunication occurrences 10 seconds before and after. I counted the total number of causal elaborations and divided it by the play time (in minutes) of each group in both conditions to calculate the frequency of causal elaboration. I made the initial coding. I then invited two independent raters to code the causal elaboration on the same subset of video clips used in the inter-subject agreement evaluation for the emotional state measure. The results showed a high agreement between raters (average Cohen's kappa = 0.92.).

Metacommunication on Object Transformation

In this study, I focused on analysing the explicit metacommunication of symbolic transformation. In particular, I was interested in investigating the difference in participants' verbal communications when transforming physical referents to objects with definite meaning, as in the role and prop selection session (e.g. "I'm a knight", "this is a car"), and to objects with open-ended meanings, as in the scenery selection session (e.g. "this is grass", "in the café"). I calculated the percentage of transformation actions with explicit verbal communications explaining the target of the transformation of the role and prop selection period and scenery selection period. The coding steps were: (1) I extracted the selection periods, which began with use of the magic wand to enter role/prop/scenery selection view and ended with use of the magic wand to exit the selection view; (2) within all selection periods, I counted the total number of metacommunication occurrences with intended selection action; (3) I counted the total number of explicit verbal communications that clarify the target object of the transformation; and (4) I calculated the percentage of selection actions associated with explicit verbal transformation communications. I did not calculate the inter-subject agreement rate since this coding method was unambiguous.

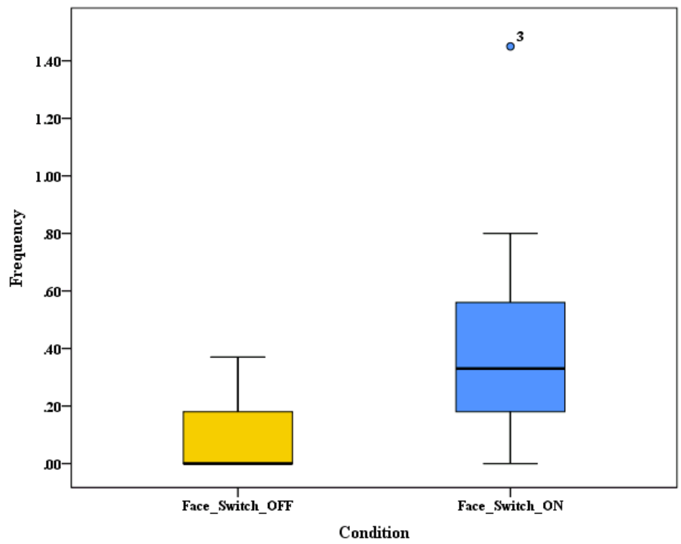
6.7 Experiment Results

I present experiment results in this section including emotional state occurrence, causal elaboration of emotion, object transformations with explicit explanation and participants' and teachers' feedback.

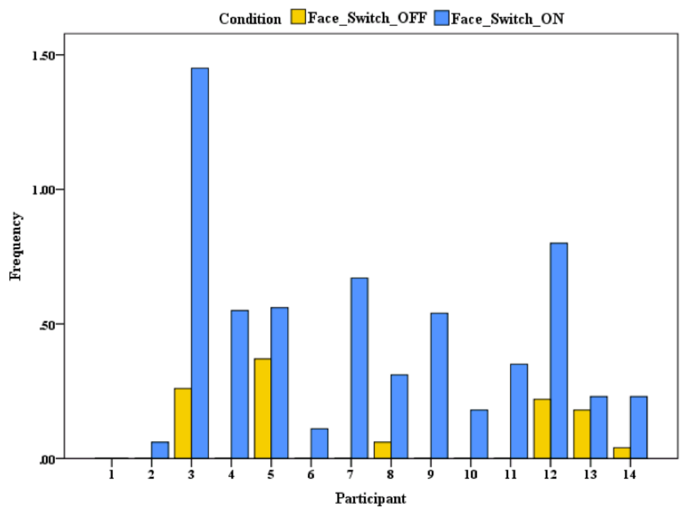
6.7.1 Emotional States

The occurrence of emotional state per minute among participants increased in the Face_Switch_ON condition (*Mean* = 0.43, *SD* = 0.37) compared to the Face_Switch_OFF condition (*Mean* = 0.08, *SD* = 0.12) (Figure 6.22(a)). The frequency of emotional state occurrence for each participant is illustrated in Figure 6.22(b). The frequency difference was statistically significant according to the paired Wilcoxon signed-rank test (Z = -3.18, $p = 0.001 < 0.01$**). The order of participants follows the group order, for example participant 1 (P1) and participant 2 (P2) were in group 1. All participants produced metacommunication involving emotional state more frequently in the Face_Switch_ON condition except for P1, who didn't generate any emotional state related play behaviour in either condition.

I summarized the number of participants that used each of the emotion terms that occurred in the study (Figure 6.23). Besides the five non-neutral facial expressions provided by the system, other emotional terms used by the participants include like, kiss, cry and love.



(a) Frequency of emotional state among participants



(b) Frequency of emotional state for each participant

Figure 6.22: Results of emotional state frequency.

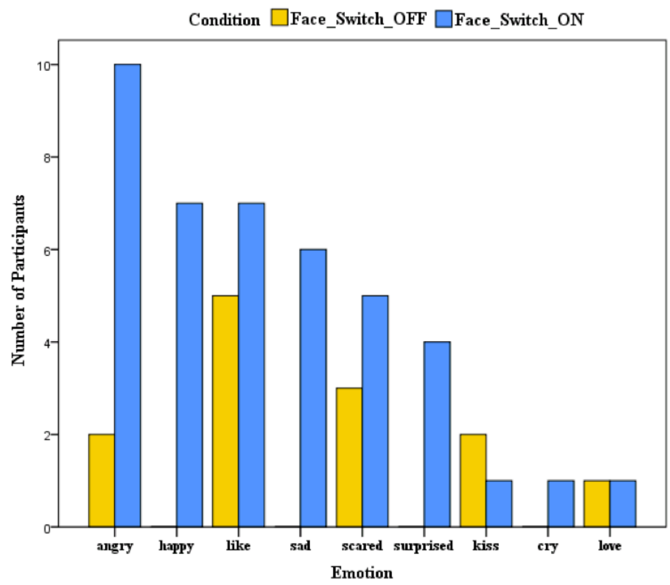
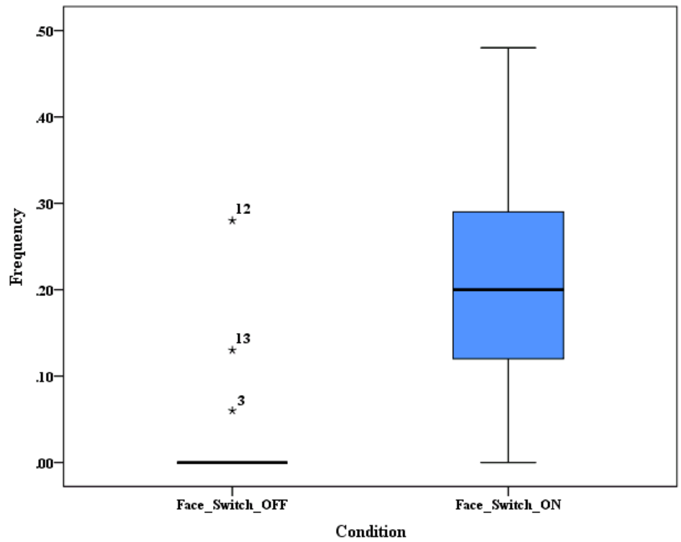


Figure 6.23: Number of participants using each emotion term.

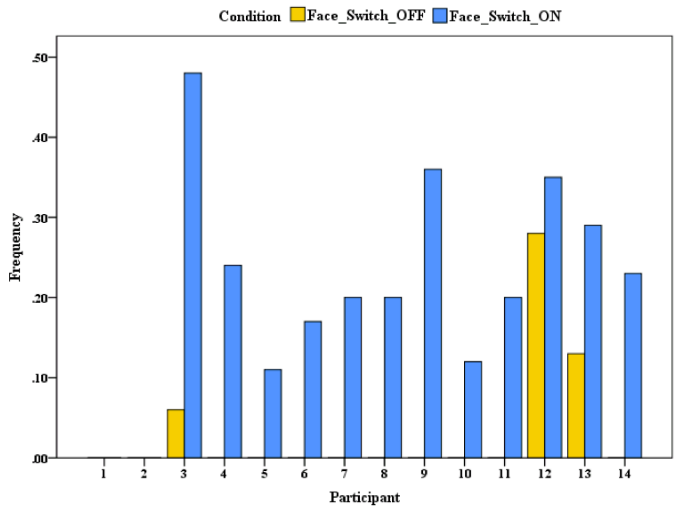
6.7.2 Causal Elaboration of Emotion

The occurrence of causal elaborations of emotion per minute of each participant was higher in the Face_Switch_ON condition (*Mean* = 0.21, *SD* = 0.13) than the Face_Switch_OFF condition (*Mean* = 0.03, *SD* = 0.07) (Figure 6.24(a)). The difference was statistically significant according to the paired Wilcoxon signed-rank test (Z = -3.06, $p = 0.002 < 0.01$**). Figure 6.24(b) illustrates the frequency of causal elaboration generated by each participant. There were only three participants that made some causal elaboration in the Face_Switch_OFF condition while there were twelve participants that produced causal elaboration in the Face_Switch_ON condition.

I summarized the number of participants that produced metacommunication involving causal elaboration of different emotion terms (Figure 6.25). It followed a similar trend to the number of participants that produced metacommunication with emotional state except that no participant managed to produce any causal elaboration relating to the emotion term "surprised". The implications of the results will be explained in the discussion session.



(a) Frequency of causal elaboration among participants



(b) Frequency of causal elaboration for each participant

Figure 6.24: Results of causal elaboration frequency.

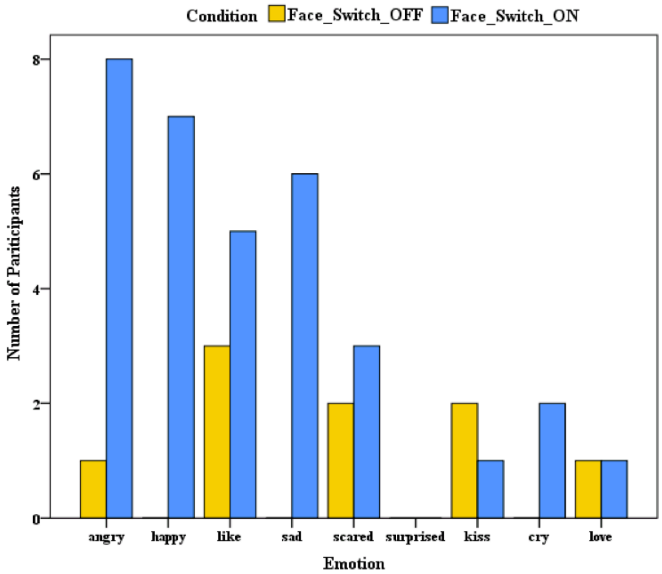


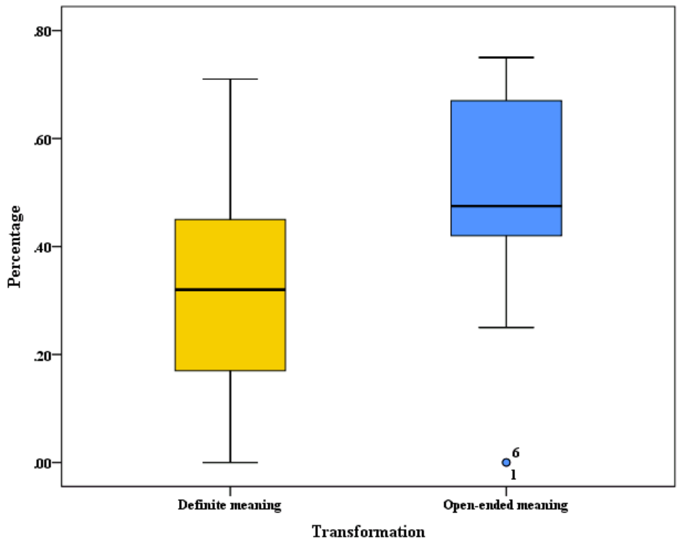
Figure 6.25: Number of participants making causal elaboration in each emotion term.

6.7.3 Verbal Metacommunication on Symbolic Transformation

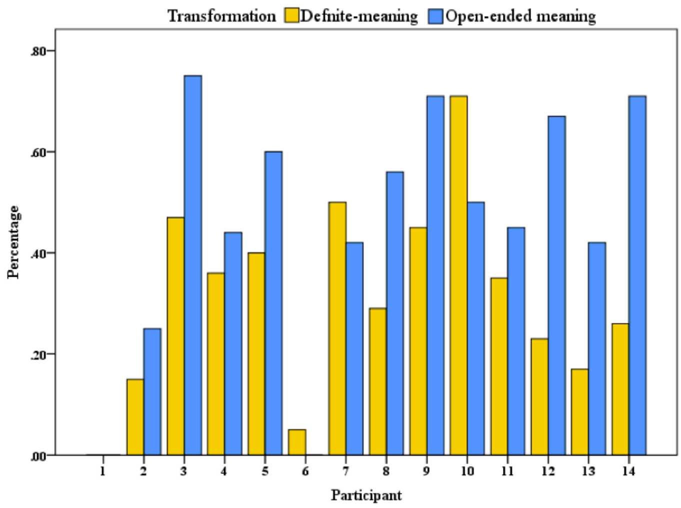
Participants made verbal communications more frequently about object transformation when choosing from open-ended representations in the scenery selection period ($Mean$ = 0.46, SD = 0.24) than the definite-meaning in the role and prop selection period ($Mean$ = 0.31, SD = 0.19) (Figure 6.26(a)). The difference in the above frequency is statistically significant among participants according to the paired Wilcoxon signed-rank test (Z = -2.45, p = 0.014 < 0.05*). Most participants produced a higher percentage of transformation actions with explicit verbal explanation in the scenery selection period except participants 1, 6, 7 and 10 (Figure 6.26(b)). I will further explain behaviours of these participants in the discussion section.

6.7.4 Divergent Ideas on Scenery Transformation

Participants carried out diverse scenery transformations with the system. I summarized representative examples based on the combination of physical referent



(a) Boxplot of percentage of verbal communication on transformation among participants



(b) Percentage of verbal communication on transformation

Figure 6.26: Results of verbal communication on transformation.

Table 6.1: Examples of scenery transformation.

	Circle	Semi-circle	Sawtooth
Green	grass, flower	grass	grass, park*
Red	fire	fire	fire
Green-red	flower		flower
Blue	swimming pool, water, sea, blue sky, big lake (with two circles combined)*		blue sky, water
White	ice rink, snow, water	snow, mountain	snow, iceberg
Brick	castle		castle wall
Black-white	racing flag, floor, café*, shield*, nurse house*		
Rock			
Golden	pancake, gold water*		
Purple		diamond	
Wood		path	
Black	black hole*		

* Symbolic ideas verbally explained in the latter play session

and open-ended representation in order to study the diversity and complexity of transformations with scenes (Table 6.1). I only included transformation ideas of scenes that were verbally confirmed by the participants to avoid ambiguity. Most of these transformations were made in the scenery selection period, with a few exceptions that participants explained the meaning of the transformation later in the play session.

6.7.5 Child Questionnaire

The majority of participants rated the play experience as brilliant in both conditions (10/14 in Face_Switch_ON and 8/14 in Face_Switch_OFF condition). This shows that the FingAR Puppet system provided a positive user experience in general. When asked which play variant was more fun, all participants named the condition with facial expression switching enabled. Some representative explanations were: "it can be sad, happy, that helps to create the story", "when the character sees a shark I can change it to shocked", "when you change the face, it changes how you feel in the story", "when it's just one face, when you're angry you cannot change the face". Most participants provided meaningful answers

Table 6.2: Answers to the teacher questionnaire.

	Nursery	Reception	Year 1
What do you think of the children's average engagement during the play?	Good	Very Good	Good
Do you think the play themes are appropriate?	Agree	Strongly Agree	Strongly Agree
Do you think the system could help guide children to plan a story in advance?	Agree	Agree	Strongly Agree
Do you think the facial expression change feature can help children portray emotion of pretend character?	Strongly Agree	Strongly Agree	Strongly Agree
Do you think the computer system could help encourage social pretend play for children?	Agree	Strongly Agree	Agree
Do you think it would be beneficial to use the system in the classroom?	Strongly Agree	Agree	Agree

when asked about things they liked about playing with the computer. Some representative answers included: "I like changing face", "I like the princess", and "I like choosing flowers", "get dragon and cannon, doing the story" and "like making a video". Participants also confirmed the structure that the system provided to help create stories: "pick character, second part (prop) whatever you want, next you choose floor, setting", "choose different things you change to different story, change different characters, you make a different theme"; "when change people, you make different story like change the setting".

6.7.6 Teacher Interview

There were three teaching assistants from the nursery, reception and year 1 classes who facilitated the study. Each of them was asked to fill out a teacher questionnaire at the end of the study (see Table 6.2). The questionnaire was followed by a structured interview. In summary, the teachers' feedback was very positive in terms of ease of use, enjoyment and facial expression switching.

6.8 Discussion

In this section, I discuss the effectiveness of the FingAR Puppet system in promoting social symbolic play in terms of emotion expression and understanding, verbal communication of symbolic transformation, and divergent thinking on scenery transformation. I then present the usability investigation of the FingAR Puppet system from observations in the experiment analysis. I identify usability issues concerning complex play activity and social interaction. I then propose potential improvements and design considerations in response to these usability issues.

6.8.1 Effectiveness of the FingAR Puppet system

Emotion Expression and Understanding

The experiment results reject the null hypotheses $\mathbf{H}_{0A}$ and $\mathbf{H}_{0B}$. This shows that the FingAR Puppet system effectively encouraged participants to express and understand emotion in a social play context. Participants produced metacommunication relating to emotional states significantly more frequently in the Face_Switch_ON condition. Participants also explained the cause and effect relationship of emotion significantly more frequently in the Face_Switch_ON condition, which shows the FingAR Puppet system not only encouraged children to simulate the emotional states of the pretend role, but also provided opportunities for them to reason about and respond to such emotion change properly. Overall, these results indicate that participants were more likely to be emotionally aware and expressive during symbolic play when they were given the ability to visually switch the facial expression of the puppet.

As shown in Figure 6.22(b), P1, P2 and P6 generated less metacommunication with emotional states than other participants. This is because they produced relatively low amounts of verbal communication during play. P3, on the other hand, was very emotionally engaged throughout the play in the Face_Switch_ON condition. There were several play episodes involving certain emotional states (kiss, love and sad) that were carried out repeatedly, which were not seen among other participants. This partially explained why P3 produced a relatively high amount of metacommunication involving emotional states.

There were nine different emotion terms that appeared in the participants' play (Figure 6.23). For these emotion terms that were used by more than three participants in the Face_Switch_ON condition, four terms were desire-based emotion (angry, happy, like, sad), and two were belief-based emotion (scared and surprised) (Ruffman and Keenan, 1996). Understanding desire-based emotions requires children to know people's desires and desirable situations, which occurs as early as two years old. On the other hand, understanding belief-based emotion requires interpreting people's beliefs, which is an ability that children do not typically obtain until about four years old. These results show that participants were more able to express desire-based than belief-based emotions, which is consistent with the existing literature discussed in Section 6.2.1. The result that no one explained the use of "surprised" indicates that participants had difficulty making causal elaborations of more complicated emotional states. This is consistent with previous findings that there is a delay with young children understanding the belief-based nature of surprise (MacLaren and Olson, 1993). It is not until seven to nine years old that children start to understand surprise as the result of false beliefs (Ruffman and Keenan, 1996). This suggests future research effort to enhance children's understanding of more complex emotion terms, such as surprised, embarrassed, proud and guilty in the social symbolic play context.

Verbal Metacommunication of Symbolic Transformation

Results show that participants verbally explained their symbolic transformation decisions during role, prop and scenery selection periods. In particular, the null hypothesis $\mathbf{H}_{0C}$ is rejected, which means participants tended to produce more verbal communication on transformations with open-ended representation in the scenery selection period, compared to definite-meaning representation in the role and prop selection period. This supported our hypothesis that participants tend to assure both themselves and their playmates about the transformation they made by verbally clarifying the target object of the transformation when associating open-ended representations to the physical referent.

There were four participants, P1, P6, P7 and P10, who produced less verbal metacommunication associated with transformation in the experiment. As discussed in the previous section, neither P1 nor P6 produced much metacommunication with their playmates throughout the play sessions. P7 was from the nursery class, and had just turned four at the time of the study. It might be more demanding for her to create meaningful things by combining physical referent with open-ended representations than choosing from those with definite-meaning. P10 was very capable at interacting with the system and more determined with the role and props that he wanted than other participants. It might be a combination of individual difference factors that caused his distinctive metacommunication behaviours on object transformation.

Divergent Thinking on Scenery Transformation

The result that participants generated diverse imaginary representations associated with the wood shapes in the scenery selection period corroborate the previous research findings that open-ended tasks are effective in promoting divergent thinking. Furthermore, I observed two major characteristics of participants' ideational behaviours relating to familiarity based on examples summarized in Table 6.1. First, participants tended to generate more imaginary representations with familiar than less familiar materials. For example many participants created grass, water and flowers by assigning green, blue and green-red materials to wood shapes respectively. They were also likely to generalize these imaginary representations to different shapes. For example, circle, semi-circle and sawtooth had each been used as grass, fire or snow. It was, however, rare to see participants creating imaginary representations beyond these obvious associations. Second, participants tended to generate more novel imaginary representations with less familiar materials. For example, they created diamonds and black holes using purple and black materials respectively. They were also more likely to interpret the same AR scenery objects differently with less familiar materials. For example, by assigning the black and white material to the circle referent, participants generated different imaginary representations such as racing flag, floor, café, shield, and nurse house. The above two major characteristics were well explained by the theory that familiar stimuli facilitate fluency of divergent thinking while unfamiliar stimuli support originality of divergent thinking (see Section 6.2.2). On the other hand, since it requires more mental effort for children to associate with unfamiliar materials, participants generated far fewer imaginary representations of scenery with less familiar materials. Overall these results show the initial effectiveness of designing open-ended representations to elicit higher levels of divergent thinking in children's imagination.

6.8.2 Usability Investigation

The usability investigation shows that the shared AR magic mirror in the FingAR Puppet system can efficiently support object manipulation and associated human-computer and social interactions in the context of social symbolic play. In this section, I first report detailed observations of user behaviours in each of the above activities in both individual and social aspects. I then examine these behaviours under major design guidance for collaborative systems in order to identify usability issues of the shared AR magic mirror in supporting social interaction. In response to these usability issues, I propose design alterations to improve the FingAR Puppet system.

Interaction Observation

Object Manipulation

Individual aspect: All participants manipulated the physical puppet properly by putting their fingers through the two holes on the bottom of the puppet, and enacted with the puppet by moving the "legs" around. This met the expectation of the FingAR Puppet, which was designed to encourage children to enact the puppets throughout the play session to emphasize role-playing and increase the chance for theory of mind practice. I only observed one participant who tried to make the puppet stand by itself during the play. For props and scenes, participants held them either with the attached grip or the body. The latter sometimes caused occlusion of the marker. I also observed that younger children tended to arrange all referents of props and scenes near themselves while older children spread these referents on the table at different depths from the screen. The outcome for the former situation was that there was intermittent occlusion. The latter arrangement sometimes caused confusion for the children between two props registered on two referents with the same shape and placed close to each other.

Social aspect: Two participants tended to split the table space evenly, and arrange physical referents only on their own side. The most common way to initiate social interaction between pretend roles was to make one puppet walk or face towards the other puppet. I observed intermittent eye contact between participants during this social initiation process.

Navigation

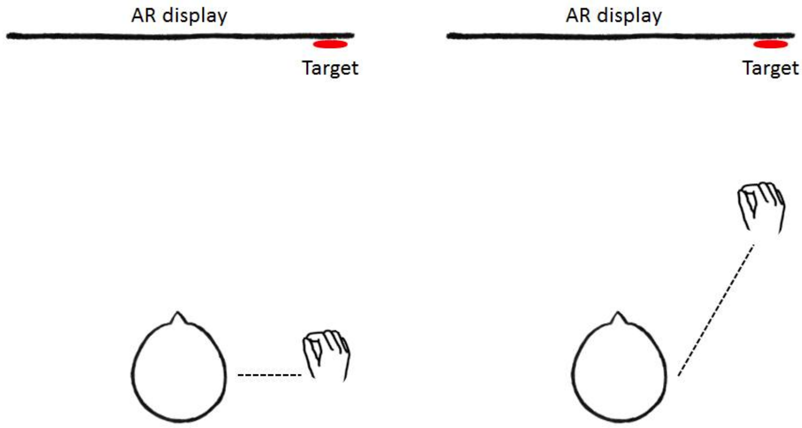
Individual aspect: All participants understood the point-to-select mechanism of using the wand to choose navigation items and could navigate properly in the navigation view, object transformation view, and play view.

Social aspect: In the navigation view, I observed that participants often took turns to select the navigation items based on the convenience to reach. In the object transformation and play views, such tacit turn taking disappeared and it required children to maintain a higher awareness of the playmates' intention and action to avoid conflicts. Observations showed that participants from reception and year 1 classes were more concerned with the playmate's intention and used both verbal and gestural cues to indicate the playmates to choose or wait, while participants from the nursery class often carried out navigation actions regardless of the playmate's behaviour. The outcomes of the latter scenario sometimes caused frustration or conflict between participants and the teacher had to assist related negotiations.

Object Transformation

Individual aspect: All participants understood the point-to-select mechanism of assigning role, prop and scenery to the physical referent. I noticed three issues for object transformation. First, participants could reach virtual items on the other side of the screen by stretching their arm or standing up, but sometimes accidentally changed to another item if it happened to be along their path as they withdrew their arm. Second, a couple of participants used mismatched physical referents for selection from time to time. For example, they might use the referent for prop selection to choose scenes, and vice versa. Third, some younger participants tended to reach out their arm towards the screen when choosing role, prop or scenery items. In this case, they subconsciously used the physical screen as the coordinate system for pointing instead of using the world coordinate system as displayed by the AR magic mirror. The immediate outcome was that these participants spent more effort reaching for items further away, because they stretched the arm in diagonal (Figure 6.27(b)) instead of parallel (Figure 6.27(a)) with the screen.

Social aspect: I noticed two interesting social interaction behaviours during object transformation. First, older participants had higher social awareness of their playmate and could help each other to choose prop or scenery items that were inconvenient to reach. Younger participants were less socially and spatially aware of the playmate. Second, all participants tended to have a strong notion of possession of virtual representations of role and props, as well as physical referents of scenery. Younger participants, however, were less able to negotiate when conflict occurred.



(a) Parallel with the screen (b) Reaching towards the screen

Figure 6.27: Illustration of participant's point-to-select behaviours using the screen as the coordinate system.

Facial Expression Switch

Individual aspect: Participants understood how to use the wand to change the facial expression of the puppet. Nevertheless, the facial expression change action was generally much more difficult compared to other interactions involved in the FingAR Puppet system. This was mainly due to the high visuomotor requirements of bimanual manipulation when both hands were free to move. According to the kinematic chain model proposed by Guiard (1987), during a bimanual manipulation task the two hands are assigned as dominant and non-dominant hand. Individuals use the non-dominant hand to set a spatial frame of reference and the dominant hand to carry out fine temporal and spatial movements relating to the non-dominant hand. Examples of such asymmetric bimanual manipulations include handwriting, sewing, and driving a screw. Most participants held the puppet with the dominant hand (right hand) and held the wand with the non-dominant hand (left hand). This might explain the additional effort in facial expression change due to poorer visuomotor ability when using the non-dominant hand for positioning.

Social aspect: According to my observation, there were seven participants who changed the facial expression of the playmate's puppet (P1, P3, P7, P11, P12, P13 and P14) under two conditions: (1) unintentionally triggered and changed the playmate's puppet's facial expression because of sitting too close to each other; and (2) deliberately changed it for fun (e.g. P3, P11 and P12). All playmates changed the facial expression of their puppet back instead of enacting or developing plots accordingly, which shows that at the current developmental stage, participants considered the facial expression change of their own puppet made by the playmate as a distraction to the social symbolic play instead of an intriguing uncertainty. Adult modelling might be essential for introducing children to this new form of emotion expression and understanding practise, especially due to its unfamiliarity compared to children's previous play experience, as one of the teaching assistants mentioned.

Usability reflections and Improvements

There is little AR research so far investigating collaborative behaviours of young children under a shared AR magic mirror involving manipulating and interacting with physical objects. Several researchers recognize spatial and social awareness as two key aspects that influence users' interaction with collaborative systems integrated with digital and physical artefacts. Hornecker and Buur (2006) articulated *spatial interaction* and *embodied facilitation* as the main concerns with supporting social interaction. Scott et al. (2003) raised a set of design guidelines for collaborative tabletop display, with two social aspects closely related to the usability of the FingAR Puppet system: *support fluid transitions between activities* and *support transition between personal and group work*. Based on the above considerations, I investigate the usability of the FingAR Puppet system in supporting collaboration in play.

Spatial Interaction

Spatial interaction emphasizes the importance of allowing users to see and follow other's actions, and communicate through body movement such as eye gaze and pointing, in order to maintain a high spatial and social awareness during collaborative interaction (Hornecker and Buur, 2006). Neglecting group members' behaviour is a common issue for a face-to-face collaborative tabletop environment, especially when it is integrated with personal displays (Rekimoto and Saitoh, 1999; Tandler et al., 2001). Since children sat side-by-side when interacting with the FingAR Puppet system, they had to perceive playmates' behaviour through the reflected view of reality shown by the AR magic mirror and peripheral perception of the surroundings. Although the FingAR Puppet provided a shared display, participants' perception and awareness of their playmate's behaviours may be affected as their images were partially occluded by the row of six selection options under the object transformation views.

Embodied Facilitation

Embodied facilitation included *embodied constraints*, *multiple access points*, and *tailored representation*, with the former two closely related to social interaction with the FingAR Puppet system. *Embodied constraints* refer to the physical setup and configurations of the collaborative system, space and objects. *Multiple access points* allow all users to get access to objects of interest, which prevents individuals taking control of the system and invites shy people to join.

First, the *embodied constraints* of the FingAR Puppet system include a shared AR magic mirror, shared tabletop workspace and physical referent, and side-by-side sitting arrangement. For the side-by-side arrangement, research shows that it is preferred by children during tabletop activities compared to the face-to-face arrangement, which is more commonly favoured by adults (Sommer, 1969). In addition, young children prefer a closer interaction distance than adults (Aiello, 1987). There were, however, two major limitations of the side-by-side arrangement for collaboration with the FingAR Puppet system. First, participants evenly split the tabletop workspace to arrange play props and scenes, which reflected the fairness characteristic of social play to avoid potential conflict (Bekoff, 2001). This behaviour to some extent prevented participants from jointly constructing play scenes as they maintained scenes separately on their own side of table. Another issue with the side-by-side seating arrangement was that it had limited support for more complex play behaviours involving more than two players.

Second, the FingAR Puppet provided abundant physical and virtual play materials for children to ensure *multiple access points*. One conflict of *multiple access points* occurred when both participants wanted to choose the same role or prop. As discussed in Section 6.3.2, this design was meant to enhance group focus and awareness (Scott et al., 2003). Observations from this study show that conflict over access to certain play materials encouraged older children to negotiate, but caused frustration for younger children who were less ready to compromise without adult mediation.

Transition between Activities and between Personal and Group Work

First, the main issue with the FingAR Puppet system relating to transition between activities that I identified was that participants spent uneven visuomotor efforts for different interactions. For example, participants referred to the near body workspace shown by the AR magic mirror as the coordinate system when carrying out object manipulation and facial expression change. Some of them, however, subconsciously switched the coordinate system to the vertical surface of the screen with navigation and object transformation interaction. Similarly, participants used play materials for the object transformation tasks but had to switch to the magic wand to navigate and change facial expressions of the puppet. These inconsistent perception and interaction factors potentially affected the fluid transition of different tasks. Second, the main issue relating to transition between personal and group work observed during this study was that during the play phase, when one participant decided to change role, prop or scenery, he or she had to navigate to the corresponding object transformation view, which unavoidably interfered with the collaborative play activities involving the other participant. In the worst case, it caused the other participant to unintentionally change the virtual content of the physical referent.

Potential System Improvements

One potential solution to improve the transition between activities and transition between personal and group work, as well as increase social awareness of other playmates is to integrate the point-to-select mechanism into a near-body interaction style as shown in Figure 6.28. The navigation, object transformation and play views are integrated into one AR view. Showing and hiding object transformation options are controlled via special anchor objects. For example, when children want to select roles, one of them puts the role transformation anchor object on the table. The FingAR Puppet system detects the anchor object and reveals a list of role options registered with the anchor object. The children can then select roles by moving the puppet close to it. Next, the child moves the anchor object off the table to dismiss the display of role options. During play, whenever one child wants to change roles, he or she can put the role transformation anchor object on the table, select the role and then put the anchor object away. This mechanism is consistent with all other selection actions including

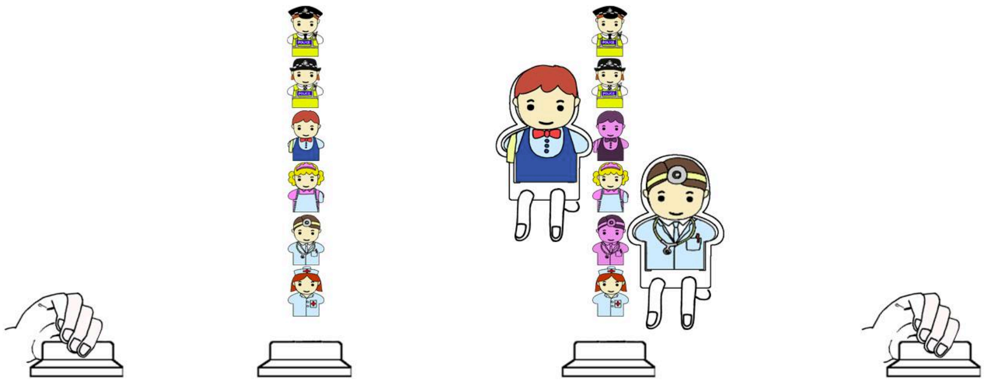


Figure 6.28: An improved approach for role transformation. From left to right: A child puts the transformation anchor object on the table; The system detects the anchor object and reveals role options registered with it; The child on the left chooses a waiter and the child on the right chooses a doctor; A child moves the transformation anchor object off the table.

prop, scenery and facial expression (Figure 6.29). An important consideration of this design is to make sure children can easily differentiate anchor objects for each type of play material.

The alternative approach presented above aims to mitigate three main usability issues discussed earlier. First, it has the potential to improve fluency of transition between activities. By adapting the point-to-select mechanism with near-body object manipulation, the new approach may reduce the coordinate system switching between the workspace and the screen. In addition, by providing a consistent interaction method between navigation, facial expression change (wand) and object transformation (play materials), it potentially lowers the mental effort to switch interaction context. Second, it has the potential to improve the transition between personal and group work. The previous interface for object transformation was appropriate for the preparation phase when both participants were engaged with the selection task. It was, however, not favourable for switching from group to personal work when one participant wanted to switch role, prop or scenery while the playmates still remained in his or her enactment. The area for the object transformation option in the proposed approach is much smaller compared with the previous interface, thus it may mitigate the impact of transitioning from group to personal work. Third, by eliminating the active area of the object transformation options, this approach potentially increases the visibility

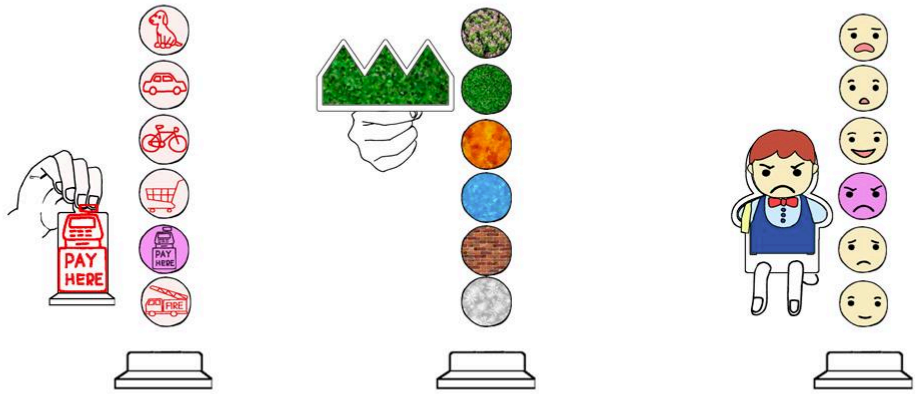


Figure 6.29: The illustration of prop, scenery and facial expression selection. From left to right: select prop; select scenery; select facial expression.

of players' image and thus raises social awareness of other players.

Another improvement in response to usability issues due to *embodied constraints* is to enlarge the tabletop workspace of the FingAR Puppet system, as shown in Figure 6.30. The curved-edge table provides an alternative user seating arrangement which may potentially improve the current FingAR Puppet system in terms of *embodied constraints* in two ways: (1) it extends the user number from two to multiple; and (2) it provides a more explicit area for group activity which potentially encourages joint construction of scenes. In order to support interaction among multiple users in a collaborative play scenario, the system has to enable a bigger field of view and more reliable tracking for clustered AR objects. Potential solutions include merging two camera views to enlarge the active table area and introducing additional cameras (e.g. top view camera) to track AR objects from multiple angles to avoid tracking being lost under occlusions.

6.8.3 Study Limitations

There are three main limitations that readers should be aware of when interpreting results of this study. First, although the study showed that participants produced metacommunication with emotional states and related causal elaborations more frequently in the Face_Switch_ON condition compared to the Face_Switch_OFF condition, most of these emotional states were desire-based. Participants were much less likely to generate metacommunication involving belief-

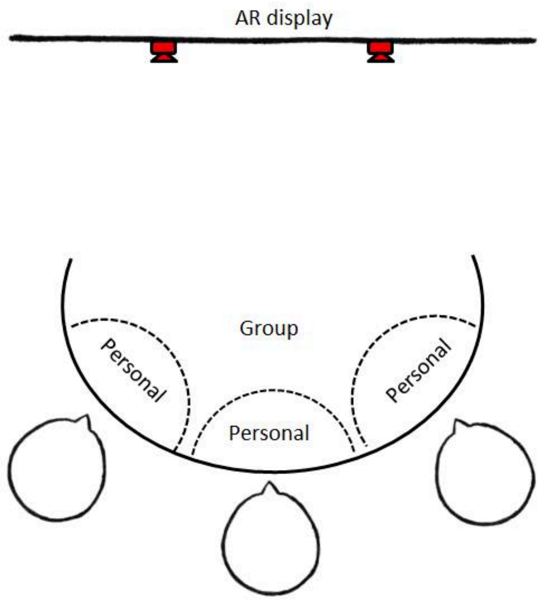


Figure 6.30: Illustration of an enlarged workspace for the FingAR Puppet system

based emotion such as surprised. This showed that the current design of the FingAR Puppet system has limited effect in encouraging social symbolic play relating to complex emotions. Second, the study only examined children interacting with the system in pairs, which represented the simplest level of inter-subject interaction and sharing of space. The limited size of the interactive space might become a potential issue when more physical objects are used by additional players. The AR magic mirror also required children to stay on one side of the table, which might require specific design considerations to support more complex patterns of social interaction among players. Third, the results of the study are based on a short-term experiment with a small sample of subjects. Although the familiarisation session on the first day was meant to eliminate learning and novelty effects of the system for the following formal sessions, the lack of previous experience with AR technologies might still play an important role in making participants highly engaged and productive in the play activities. A long-term study with more subjects is needed in the future to examine the lasting effect of the FingAR Puppet system in helping children progress over time with more complex emotional states and creative symbolic transformation.

6.8.4 Future Work

Besides work mentioned in the study limitation and usability improvement sections, I would like to extend our study in the following aspects. First, I would like to observe children's different social symbolic play behaviours between using the FingAR Puppet system and in an equivalent natural play setting without computer assistance, in order to further our knowledge of the strengths and weaknesses of AR technologies in play contexts and obtain further improvement implications. Second, it will be interesting to examine potential benefits of the FingAR Puppet system to help children with ASC, who often have difficulties in both imagination and social interaction, to develop related skills. Certain adaptations of system design will be required considering restricted interests and impaired social understanding among children with autism, such as enabling children and adults to efficiently include new virtual and physical materials to the AR system, as well as extending AR scaffoldings from emotional states to more complex desire and belief-based mental states that are difficult for autistic children to understand in spontaneous social contexts due to delayed socio-cognitive development. Third, I need to investigate solutions for a few usability issues such as unintentional change of facial expression and object transformation, marker occlusion when holding the physical objects inappropriately, and mismatch of object in the selection periods. Fourth, I would like to find ways to encourage children to explore more complex, belief-based emotions such as surprised, embarrassed, and proud in their play. Fifth, I would like to look into ways to enable both adult and child users to extend the content of the current system, including role, prop, scenery and facial expression. It is essential for children to constantly engage and progress with the FingAR Puppet system as their socio-emotional experience and play interests develop.

6.9 Conclusions

In this chapter, I presented the theoretical grounding, design and evaluation of the FingAR Puppet system, which was intended to provide a fun and enhanced social symbolic play experience for preschool children. Observations showed that children were highly engaged with the FingAR puppet system. Specifically, the experiment results confirmed that (1) AR is helpful to externalize the cognitive processes of symbolic thought by enabling children to manipulate symbolic transformations from physical representations to imaginary representations; (2) the facial expression switching feature encouraged children to express and understand emotion in response to social context in stories; and (3) the open-ended representation in the scenery selection period encouraged children to create diverse symbolic transformations and more actively communicate such ideas with the playmate to construct joint pretense, compared to representations with definite meaning in the role and prop selection periods. I further discussed the implications of the results, usability findings as well as study limitations and intended future work.

The design and evaluation of the FingAR Puppet system contributed to answering the two research questions in terms of design and usability considerations of AR magic mirror to enhance social symbolic play for young children. First, the design of the FingAR Puppet system integrated essential elements of social symbolic play including role, props, scenery and emotion into the three-level AR stimuli structure proposed in Chapter 3. Findings of the empirical experiment confirmed the following design considerations: (1) level-2 AR stimuli were effective to support symbolic thought conception by facilitating children to initiate object transformation from physical referents to a pre-defined set of imaginary representations. In particular, stimuli of this level showed positive effect in supporting theory of mind practices by applying this transformational process to emotion expression and understanding of pretend roles during play; (2) level-3 AR stimuli were effective to support verbal metacommunication of joint pretense and divergent thinking during social symbolic play by helping children to conceive imaginary representations from open-ended materials. Observations of scenery transformation showed that participants tended to generate a greater number of imaginary representations with familiar materials, but more novel imaginary representations with unfamiliar materials.

Second, observation of the FingAR Puppet usability confirmed that the AR magic mirror efficiently supported complex play activities and social interactions involved in social symbolic play. I summarized primary usability considerations of the AR magic mirror to support complex play activities, which include: (1) a consistent coordinate system for visuomotor tasks was essential to enable fluent transition between manipulation of play materials and facilitative interactions such as navigation and object transformation; (2) bimanual manipulation had to comply with the asymmetric division of dominant/non-dominant hand, and free movement of the non-dominant hand should be avoided to ensure finer position performance. Furthermore, usability considerations of the AR magic mirror to support social interactions include: (1) a constrained active area for personal activities is important to eliminate interruption to group play activities; (2) consistent visibility of all users' images is important to raise and maintain social awareness among players; and (3) an explicit group area is useful to facilitate collaborative construction of play scenes and large field of view of the AR magic mirror was the basis to enable the division of personal and group activity areas.

These above design and usability considerations provide basic design guidelines for future AR systems applying the AR magic mirror to enhance shared symbolic and creative play experiences, which involves manipulating and communicating about physical play materials among children of preschool or early primary school age, especially those under the autism spectrum who often show difficulty in sharing imaginative play with peers.

Chapter 7

Conclusion

This thesis set out to address the overall research goal of using AR to promote cognitive and social development in symbolic play for young children with and without ASC. This research goal was proposed based on an integrated literature review considering the importance of symbolic play in early childhood and the representational analogy between AR and symbolic play. I regarded symbolic play as a fruitful research topic due to its primary characteristics including representational mental processes, physical object manipulation, and complex tasks for young children with and without ASC. Enhancing symbolic play effectively explored these characteristics, and thus contributed to our knowledge of the representational potential of AR, affordance of the AR magic mirror and rigorous evaluation methods for AR systems in supporting complex activities for special user groups.

In seeking to answer the research questions of this thesis, I performed a series of theoretical and empirical studies with escalating research focus and scope. In the following sections, I elaborate the conclusions I have reached based on the findings accumulated through these studies. In Section 7.1, I outline major findings in response to the overall research goal and research questions. In Section 7.2, I discuss the contributions and related implications resulting from these findings. In Section 7.3, I discuss main limitations of these studies and in Section 7.4, I provide directions for future research. Finally, I conclude this thesis in Section 7.5.

7.1 Summary of Findings

In Chapter 3, I elaborated the representational analogy between AR and symbolic play and proposed a three-level AR approach to progressively promote symbolic play. In Chapter 4, I presented a preparatory study of the usability of the AR magic mirror to support visuomotor tasks involving bimanual manipulation of physical objects. In Chapter 5, I designed and evaluated an AR system that promotes solitary symbolic play for young children with ASC. In Chapter 6, I designed and evaluated the FingAR Puppet system that promotes social symbolic play for typically developing young children. The main findings were summarized within the respective chapters. In this section, I integrate these findings to answer the overall research goal and research questions of this thesis.

Overall Research Goal:

Explore to what extent AR can promote cognitive and social development in symbolic play for young children with and without ASC.

The empirical findings of Chapters 5 and 6 confirmed the positive effects of AR in promoting cognitive and social development in symbolic play. In particular:

1. AR has positive effects to elicit solitary symbolic play for young children with ASC of preschool and early primary school age.

   The AR system designed in Chapter 5 encouraged children with ASC aged 4-7 to produce symbolic play with higher frequency and longer duration, compared with an equivalent play setting without computer assistance. The findings also show the AR system supported children to produce diverse play acts and adapt to different play themes in spite of their restricted play interests. Moreover, findings of individual differences show a graduated effectiveness of the AR system for children of different autistic conditions, with the most positive effects on children who had the most developmental delay in symbolic play.

2. AR has positive effects to elicit social symbolic play for typically developing children with preschool and early primary school age.

The FingAR Puppet system proposed in Chapter 6 promoted social symbolic play of typically developing children aged 4-6 by encouraging them to express emotional states of pretend roles in a social context, explain the cause and effect relationship of these emotional states, generate divergent symbolic transformations with open-ended AR play materials, and actively communicate about these symbolic transformations with playmates to construct joint pretense.

Research Question 1:

What are key design considerations of AR systems that promote symbolic play for young children with and without ASC?

I investigated design considerations based on two research projects using AR technologies to support symbolic play for young children with varied cognitive abilities. I described the core design concept of using AR to promote symbolic play in Chapter 3, as well as detailed design of two different AR systems that progressively apply this core design concept in Chapters 5 and 6. With the confirmed effectiveness of both AR systems, I identified three primary design considerations of AR systems to support early child development through play: cognitive mechanism, gradual development and play interest.

1. Cognitive mechanism
   The cognitive mechanism of symbolic play informs the analogy between AR and symbolic thought, and the causal relationship between symbolic thought and both theory of mind and divergent thinking in our study. This indicates that an in-depth review of the cognitive mechanism of target play activities is essential to help identify the special strength of AR to support certain cognitive processes beyond simple motivational factors. In addition, such a review enables researchers to understand the connection of the core cognitive processes to other important developmental abilities associated with the play activity, thus unfolding potential opportunities to maximize the effectiveness of AR to promote child development.

2. Gradual development
   AR systems that aim to enhance cognitive processes of young children have

to be designed through the lens of gradual development in early childhood. Since there is a general variation of individuals' cognitive abilities around the optimal level within a certain age range, a sustainable design strategy is required to accommodate needs of children with diverse developmental abilities. In particular, the progressive AR design approach in this study suggests a gradual increase of mental effort required to conceive symbolic thought as a sustainable strategy to accommodate general variation of individuals' cognitive abilities.

3. Play interest
   While the progressive AR design approach provided the essential strategy to elicit cognitive and social processes, the play contents realised this concept in a concrete representation to motivate children's engagement with the AR systems. Applying individual interest has been considered an effective approach to increase motivation of appropriate play behaviour, especially for children with ASC who often show restricted interests on certain topics. We therefore reckon play interests of children in different developmental stages as important references to guide the design of detailed play contents for AR systems.

Research Question 2:

How usable is the magic mirror display metaphor in supporting object manipulation in symbolic play?

The empirical findings from Chapters 4, 5 and 6 cumulatively confirmed that the magic mirror display metaphor is appropriate to support fundamental visuomotor tasks involving bimanual manipulation of physical objects and related human-computer and social interactions for young children with and without cognitive and motor developmental delays.

1. Findings from Chapter 4 show that adult users can perform bimanual manipulations of physical objects with comparable speed, accuracy and preference under the AR magic mirror compared with the see-through window display. These preliminary results clarified the limited impact of mirror reversal regarding complex object manipulation in three-dimensions, and

thus indicates the AR magic mirror as an alternative display with high accessibility to support bimanual manipulation of physical objects at home and in the classroom.

2. Findings from Chapter 5 show that autistic children with fine motor difficulties as young as four years old can manipulate physical objects under the AR magic mirror in terms of grasping, translation, rotation, combination and containing. This indicates that children are able to adapt visuomotor skills to an AR magic mirror coordinate system within a short period of time.

3. The study in Chapter 6 extended physical object manipulation to more complex human-computer and social interactions with the AR magic mirror. The findings reaffirmed that typically developing children as young as four years old can efficiently interact with the AR magic mirror in pairs with interaction methods more complex than those in Chapter 5. Furthermore, the findings show that the AR magic mirror is promising to support basic social interaction and social awareness in collaborative play activities.

Furthermore, I identified major usability issues observed during studies in Chapters 4, 5 and 6, which lead to the following considerations when applying the AR magic mirror to support activities involving physical object manipulation and associated human-computer and social interactions in future AR applications. Implications to mitigate these usability issues are discussed in the next section.

1. Depth perception

   Findings in Chapters 4, 5 and 6 reveal that both adult and child users do not have confusion with left/right and up/down movements. The inclusion of body image in an AR magic mirror was beneficial to provide a strong cue of upright orientation. The child users, however, needed extra visuomotor effort to relate objects along the inward/outward dimension of the screen, which agreed with existing psychology literature of depth perception confusion caused by mirror reversal. Intermittent eye gaze switching from the screen to the workspace is expected when children reassess the spatial relationship between physical and/or virtual objects.

2. Coordinate system

Findings in Chapter 6 show that when virtual objects were registered with physical referents, children mainly referred to the near-body coordinate system reflected by the AR magic mirror during interaction. On the contrary, when interactive virtual objects were purely rendered on the screen without being registered to physical referents, children tended to refer to the screen as the coordinate system and ended up subconsciously stretching their arm towards the screen during the interaction. This may introduce greater motor effort compared to the near-body interaction style.

3. Bimanual manipulation

   Findings in Chapter 6 show that children were less capable with the bimanual manipulation involved in the facial expression switching task compared with other bimanual manipulation with relational tasks on the table surface. This reflected visuomotor difficulties for young children when both hands are free to move, and the non-dominant hand is required to carry out fine positioning tasks.

4. Social collaboration

   Findings in Chapter 6 show that children could interfere with the other player by either controlling the system flow without paying attention to the other player's intention or action, or changing the facial expression of the other player's puppet. In addition, children tended to split the workspace and maintain scenes separately on each side of the table, which did not properly encourage them to jointly construct play scenes.

Research Question 3:

What are key considerations to rigorously evaluate the effectiveness of AR in promoting symbolic play for young children with and without ASC?

In Chapter 5, I identified existing experiment methods and specific developmental symptoms as key considerations when conducting rigorous evaluation of the effectiveness of AR systems in supporting symbolic play for children with and without ASC. First, symbolic play involves complex and flexible cognitive processes. It is, therefore, challenging to accurately identify symbolic play acts and evaluate the immediate effectiveness of AR elicitation within a short period of time. The study in Chapters 5 and 6 demonstrated the importance of referring to experiment methods applied in existing developmental psychology literature as design guidance of measurement methods and coding scheme for reliable quantitative evaluation. Second, children with ASC experience heterogeneous symptoms that pervasively affect their behaviours in unfamiliar situations. In order to minimize potential adversities for children to participate in controlled experiment and ensure the evaluation validity, the following key characteristics of ASC have to be carefully integrated into the experiment design of the AR system.

1. Restricted interests and activities:
   It is recommended to introduce familiarization sessions before the experiment sessions to allow participants to explore the augmentation mechanism of AR technologies in order to mitigate their obsessive interest with computers commonly seen among children with ASC. In addition, it is helpful to design visual support for parents to describe the study to their children and guide the participants through task transfer in order to mitigate anxiety and resistance of autistic children when exposed to new activities and environments.

2. Impaired communication:
   It is helpful to determine the minimal requirement of communication abilities for participants to follow simple instructions during the experiment. If possible, collect feedback from caregivers in advance to make sure the instructions are comprehensible to their children. In addition, empirical findings in Chapters 5 and 6 show that the Fun Toolkit is a useful visual support to help children with ASC as young as four years old to communicate their opinions, something which has only been applied for much older autistic children in previous research.

3. Additional atypical sensory sensitivities and individual differences:
   It is critical to avoid unnecessary distractions caused by pervasive atypical sensory sensitivities such as touch, auditory, and visual during the experiment. Furthermore, exploring individual differences of performance during the experiment, which helps to predict the outcome of relevant intervention in a larger population with different subgroups of individuals.

7.2 Contributions and Implications

In this section, I outline the main contributions of this thesis based on findings with respect to the research goal and research questions, and elaborate related implications on existing theories and understandings.

Contribution 1:

Confirm the positive effects of AR in promoting symbolic play for young children with and without ASC.

Studies in this thesis confirmed the effectiveness of AR to enhance symbolic thought, theory of mind and divergent thinking in symbolic play. These empirical findings are informative for both developmental psychologists and AR researchers.

First, this thesis provided an alternative AR approach to promote symbolic play in response to major limitations of traditional intervention methods. The AR approach provided a special way to visually illustrate the representational and transformational mechanism of symbolic thought, which are otherwise opaque and difficult to explain to young children with ASC, who are either impaired with such cognitive mechanisms or have difficulty to translate symbolic thought into play acts. Moreover, the enhancement of symbolic thought also closely contributes to theory of mind and divergent thinking development, both of which are important for one's later life but largely neglected in conventional interventions.

Second, this thesis advanced our knowledge of the representational capacity of AR to support complex cognitive processes. The AR approach explored in this thesis pertains to exploiting the dual representation characteristic of AR to foster the development of symbolic and divergent cognitive processes based on existing knowledge that children possess. In contrast, the majority of operational task-support or educational AR applications concern optimising users' access to existing knowledge without stretching the actual cognitive processes. Moreover, the theoretical root of using AR to support the dual representation of pretense demonstrated the importance of the representational feature of physical objects in an AR environment, which is largely overlooked among AR and tangible applications for children play. This is because physical objects involved in most of these applications are used either by their literal meanings, or simply as tangible entities to enable children to manipulate virtual objects. This thesis, therefore, extended our knowledge of opportunities with highly integrated AR interfaces that inherit the rich expressiveness of both virtual and physical in a meaningful way to support complex cognitive processes.

Contribution 2:

Provide a progressive AR design approach to promote symbolic play for young children.

The design processes of the three-level AR approach and its application to the two AR systems developed in this thesis advanced our knowledge of (1) tailoring AR representations for children with different developmental abilities; (2) the potential of AR to ease skill transfer to reality; and (3) the design space of open-endedness to enhance symbolic and divergent cognitive processes.

First, AR systems developed in this thesis function as bi-directional bridges between the mind and the physical world to enhance target mental processes during symbolic play. The level-1 stimuli focus on helping children internalize the representational and transformational mechanism of symbolic thought while level-2 and level-3 stimuli focus on inducing children to externalize their symbolic thoughts on the physical world. The three-level approach requires a gradual increasing of mental efforts to conceive symbolic thoughts, which accommodate the discrepancy of cognitive abilities among children with different developmental states and difficulties. This progressive AR design approach extends our understanding of the design space of graphical representations to enhance external cognition for learning.

Second, AR activates certain objects and areas in the physical world for symbolic transformation, which makes the familiar environment inviting for symbolic play. Once children become adept at the non-literal way of interpreting aspects of physical surroundings activated by AR elicitations, they are more likely to extend such interpretations towards other aspects of the environment, and continue with similar symbolic play behaviours even after the visual elicitations are switched off. This close relationship with reality is considered as the special advantage of AR technologies over other computer technologies such as VR to help children associate skills and experience obtained from the computer environment to daily life. Although this thesis did not explore the above generalization effects due to limited research resources, findings in Chapters 5 and 6 are informative for future studies involving long-term intervention and a larger sample size.

Third, the design of open-endedness is another important implication of the AR design approach proposed in this study. The approach has an emphasis to motivate progressive open-endedness of symbolic thought. This was implemented by an escalating degree of flexibility with the combination of symbolic representation and symbolic transformation. Supporting open-ended symbolic play is an important advantage of AR compared with verbal or physical prompting in traditional interventions because it maximizes independence and divergence for symbolic thought. Findings in Chapter 6 illustrate design opportunities of manipulating ambiguity of physical and virtual representations to reinforce divergent thinking and inter-subject communication on conception of imaginary representations as part of symbolic thought.

The main challenge of the open-ended AR elicitation is to encourage children to stretch their mental efforts to exercise symbolic thought with less familiar scaffoldings. Findings in Chapter 6 show that children produced fewer symbolic thoughts relating to belief-based emotion and unfamiliar scenery materials because of the additional mental efforts required. It is, however, especially beneficial to encourage children to carry out these additional mental efforts, because belief-based emotion involves a higher level of theory of mind than desire-based emotions and unfamiliar materials tend to elicit more novel symbolic transformations than more familiar materials. Since children are more likely to choose familiar scaffoldings, designing open-ended AR play environments that induce children to engage in more demanding mental processes remains challenging.

Contribution 3:

Confirm the usability of the magic mirror display metaphor to support physical object manipulation, and associated human-computer and social interactions.

Bimanual manipulation of physical objects is commonly involved in AR systems with HMD that apply the see-through window display metaphor, but it is rarely explored under the support of the AR magic mirror. The investigation of using an AR magic mirror to support symbolic play filled the knowledge gap with respect to the usability of AR magic mirror for physical object manipulation and related user interactions. This thesis demonstrated that young children with limited cognitive and motor abilities efficiently performed interactions via physical object manipulation and carried out social interactions with an AR magic mirror. These findings indicate that the AR magic mirror is promising in supporting physical object manipulation for more capable users, and thus demonstrates new application opportunities of the AR magic mirror beyond traditional scenarios of augmenting virtual contents on the human body or interacting with virtual objects through gestures of body parts. I identified several potential improvements to enhance usability of the AR magic mirror in respective chapters, and I summarise major considerations below:

1. Physical object manipulation
   To minimize the orientation confusion of object movement caused by depth perception in the mirror view, an AR magic mirror should avoid encouraging object movement non-parallel to the screen, and provide physical referents for interactive virtual objects to which children can refer when uncertainty of spatial relationship occurs.

2. Complex interaction
   To ensure efficiency of different types of interactions and keep transitions between these interactions fluent, an AR magic mirror should keep a high consistency of the coordinate system to which children refer. In particular, near-body interaction style is recommended to ensure fine visuomotor performance for young children. Furthermore, to ease the effort of bimanual manipulation, an AR magic mirror should comply with the asymmetric division of dominant/non-dominant hand and avoid requiring the child to use the non-dominant hand for fine positioning tasks, especially when both hands are free to move.

3. Social interaction
   To elicit and maintain social awareness of the intention and action of other playmates, an AR magic mirror should ensure consistent visibility of images of all users. Moreover, to encourage social collaboration while eliminating interruption between personal and group activities, an AR magic mirror should constrain the active area for personal activities and maintain an

explicit area for group activities. A large field of view is required to enable the division of activities areas for multiple user collaboration.

Contribution 4:

Outline key considerations for rigorous evaluation of AR systems in supporting tasks that involve complex cognitive processes and young children with ASC.

As AR technologies mature, there have been increasing research efforts to seek new opportunities of AR applications beyond helping users to complete operational tasks in shorter time and with higher precision, and towards facilitating tasks involving more complex cognitive, social and affective processes for users with a wide range of demands. Existing evaluations of these latter AR systems, however, mostly focus on qualitative user feedback and observation, with quantitative evaluation of effectiveness under-explored. As discussed in the evaluation challenges for AR applications for children, quantitative evaluation can efficiently bridge discussion between computer scientists and domain experts such as developmental psychologists and educationists, which is essential to initiate cross-disciplinary research efforts involving multiple iterations and long-term evaluations on a large sample base.

In this thesis, I developed a rigorous evaluation approach for symbolic play as a representative activity that involves complex and flexible cognitive processes of children with diverse and limited abilities. This approach demonstrated the value of using established literature in relevant disciplines as reference resources for designing rigorous evaluation methods for cognitive process enhancement under AR elicitations, and accommodating developmental factors of young children with pervasive developmental symptoms to ensure success of participation during experiments. Moreover, it is critical to gather sufficient developmental information of child participants in order to take individual differences into consideration when analysing detailed effectiveness of the proposed AR system. Empirical findings derived from this analysis provided valuable information for external researchers and designers to predict potential user groups that may benefit most from the AR facilitation. Although this rigorous evaluation approach was initially proposed for evaluating AR systems, it is potentially applicable to general computer systems with novel user interfaces.

7.3 Limitations

The limitations of each study in the thesis were discussed respectively in each chapter. I summarise the major limitations shared among these studies, which lead to a more comprehensive understanding of findings in these studies and directions for future study.

1. Small sample size

   All three empirical experiments involved a relatively small set of participants, which may affect the confidence of the empirical findings to some extent. This was mainly due to limited experiment resource, especially scarce availability of children with ASC. Besides, it is common to have a small sample size of 8-15 participants for studies involving special user groups in HCI studies. I consider empirical findings of this thesis as important and timely preliminary indications for future studies with larger user groups.

2. Lack of long-term evaluation

   The experiments in Chapters 5 and 6 aimed at evaluating the immediate effects of AR to elicit symbolic play. Results from short-term evaluation are limited to inform effectiveness in two main aspects. First, the generalization effect of the AR system to encourage spontaneous symbolic play in natural play settings needs to be addressed under long-term exposure and formal pre-/post-assessments. Second, although the familiarisation session was introduced to reduce the novelty effect of the system, since most children do not have previous experience with AR, long-term observation is needed to observe the lasting effect of AR as novelty fades out.

3. Lack of comparison between autistic and typically developing children

   This thesis did not compare the play performance between autistic and typically developing children with matched mental and verbal abilities, as often included by psychology research. The experiment in Chapter 5 did not include such comparisons because unlike children with ASC, typically developing children do not encounter difficulties in spontaneous symbolic play, and a non-significant difference was observed in the pilot study. In spite of the limited enhancement space for typically developing children, such comparisons may still be informative for the design of future AR systems, and reveal symbolic play difficulties of children with ASC from an alternative perspective. The experiment in Chapter 6 did not include such comparisons due to the project schedule and limited access to children with ASC. It is considered an essential study in the future to investigate to what extent the FingAR Puppet system can enhance social symbolic play for children with ASC.

7.4 Directions for Future Studies

In addition to future studies addressing the study limitations outlined above, findings of this thesis inform researchers in fields such as AR and HCI to seek AR approaches to further enhance cognitive and social development for young children. I identified the following aspects as research extensions from this thesis:

1. Elicit comprehension of more complex mental states

   I chose emotion as the target mental state to be enhanced in this thesis because comprehending others' emotion is one of the earliest forms of theory of mind, and it is associated with overt visual and vocal cues. Future studies are needed to explore approaches that help children to understand and exercise more complex emotional states such as surprise and embarrassment, as well as subtle and hidden mental states such as belief and desire.

2. Explore design space for open-endedness

   Findings in Chapter 6 show that integrating ambiguous physical and virtual materials can encourage divergent thinking and metacommunication. This indicates new research direction to design open-ended AR materials and integrations to encourage children to creatively externalize symbolic thought to familiar surroundings. In addition, it is worth exploring approaches to facilitate children and adults to efficiently include new virtual and physical materials to the AR system, in order to better sustain children's ever-developing knowledge and interests.

3. Explore symbolic play enhancements under other AR displays

I chose the AR magic mirror as the fundamental AR interface in this thesis because of its suitability to support symbolic play and the gap of knowledge of its capacity to support physical object manipulation. Since the dual representational feature of AR has been demonstrated to have positive effects in promoting symbolic play, further studies are expected to extend the design space of symbolic play enhancement using other AR displays such as see-through windows or projection-based displays, with emphasis on their advantages over the AR magic mirror such as direct view, higher mobility or larger field of view for social interaction.

7.5 Conclusion

The distinct characteristic of AR that seamlessly integrates virtual and physical representations constantly draws researcher's attention to extend our understanding of the capacity of AR to improve quality of human life in many aspects. Identifying the representational analogy between AR and symbolic play, I developed a progressive AR design approach to support complex cognitive and social processes of symbolic play for children with limited and diverse developmental abilities. I then combined this AR approach and relevant psychology literature to guide the design of two proof-of-concept AR systems that promote solitary and social symbolic play respectively, with emphases on symbolic thought, theory of mind and divergent thinking enhancement. To develop rigorous evaluation methods for the effectiveness of these AR systems, I extensively referred to established psychology literature on symbolic play and characteristics of ASC. Empirical findings confirm that AR has positive effects to promote symbolic play for children with and without ASC in preschool and early primary school age.

The empirical results and corresponding considerations during the design and evaluation of these AR systems progressively address the overall research goal and research questions of this thesis. First, this thesis provides an alternative educational tool to illustrate and encourage symbolic play for children with diverse developmental abilities. Second, this thesis extends our understanding of the capacity and design space of AR to influence complex cognitive and social processes. Third, this thesis fills the knowledge gap of AR magic mirrors in supporting physical object manipulation and associated human-computer and social interactions. Lastly, this thesis demonstrates a rigorous approach to apply interdisciplinary literature to guide the design of evaluation methods of AR systems involving complex cognitive processes and special user groups.

Symbolic play, as a capsule of key cognitive and social developments in early childhood, provides a fruitful user scenario for AR. The joint understanding of AR technologies and cognitive processes of symbolic play fostered the identification, design and evaluation of proof-of-concept AR systems to promote symbolic play. In turn, findings through these research efforts informed the essential inquiries of the strength of AR to guide complex cognitive processes that are important but demanding for users with certain cognitive limitations. As a result, this thesis provided timely theoretical and empirical exploration of the connection between representational characteristics of AR and fundamental mental processes pertaining to altering the perception of reality, and thus illuminated directions of future studies.

Appendix A

Experiment Materials of the Chapter 4 Study

A.1 Consent Form

A.2 Questionnaire

Computer Assistance Experiment Consent Form

Experiment Purpose & Procedure

The purpose of this experiment is to evaluate the usability of two versions of the same computer assistance systems.

The experiment consists of two sessions and it will require approximately one and half hours of your time. In session #1, the researcher will demonstrate how to use the first version of the system. Then you have about 10 minutes to go through a demo task yourself. After that you will be asked to finish three tasks similar with the demo task. In session #2, you will go through the same procedure with the second version of the system. You will have 15 minutes break between each session. After the experiment, you will be asked to complete a questionnaire.

Please note that none of the tasks is a test of your personal intelligence or ability. The objective is to test the usability of the two different computer assistance systems.

Confidentiality

All data will be coded so that your anonymity will be protected in any research papers and presentations that result from this work.

Finding out about results

If interested, you can find out the result of the study by contacting the researcher, Miss Zhen Bai, after 1st May, 2011. She can be contacted in room SS06, Computer Laboratory, University of Cambridge, 15 JJ Thomson Avenue, Cambridge CB3 0FD. Her phone number is 01223763626 and her email address is zb223@cam.ac.uk.

Consent

Your signature below indicates that you have understood the information about the computer assistance experiment and consent to your participation. The participation is voluntary and you may refuse to answer certain questions on the questionnaire and withdraw from the study at any time with no penalty. This does not waive your legal rights. You should have received a copy of the consent form for your own record. If you have further questions related to this research, please contact the researcher.

________________________________	____________________________
Participant	Date
________________________________	____________________________
Researcher	Date

Questionnaire

Participant # ______________

Version #1 ___________ Version#2 ______________

----

1. Gender
   □ Male □ Female

2. Age
   □ 15-25 □ 26-35 □ 36-45

3. Experience with solving a Rubik's Cube
   □ None □ Beginner □ Intermediate □ Expert

4. How easy was it to follow the visual instructions with each version of the system?

	Very Easy	Easy	OK	Difficult	Very Difficult
Version #1	□	□	□	□	□
Version #2	□	□	□	□	□

5. With which version of the system do you think you respond to the instructions quicker?

   □ Version #1 □Version #2

6. With which version of the system do you think you make fewer errors in general?

   □ Version #1 □Version #2

7. How confident do you feel while following instructions of each version of the system?

	Very Confident	Confident	OK	Unconfident	Very Unconfident
Version #1	□	□	□	□	□
Version #2	□	□	□	□	□

8. Physically, how comfortable were you while interacting with each version of the system?

	Very Comfortable	Comfortable	OK	Uncomfortable	Very Uncomfortable
Version #1	□	□	□	□	□
Version #2	□	□	□	□	□

9. Which version of the system do you feel is more natural to use?

   □ Version #1 □Version #2

Appendix B

Experiment Materials of the Chapter 5 Study

B.1 Consent Form

B.2 Visual Support to Introduce the Study

B.3 Parent Questionnaire

B.4 Child Questionnaire

UNIVERSITY OF CAMBRIDGE
Computer Laboratory

Zhen Bai
PhD Candidate

Experiment Consent Form

Experiment Purpose & Procedure

The purpose of the experiment is to compare children's pretend play behaviours between natural and Augmented Reality (AR) environment. The experiment consists of two sessions and each session requires about half an hour. In one session, the child will be asked to play with a bunch of physical props under certain play themes. The experimenter will name the play theme and ask the child to act it out. In the other session, the child will be asked to play with the same set of props while using the AR computer system. The experimenter will instruct the child about how to interact with the computer system and name the play theme for the child to act out. There will be a half to one hour break between the two sessions. During each session, the parent or guardian is asked to observe the child playing and rate the play engagement level. At the end of each session, the child will be asked to answer two questions about his or her play experience. After the experiment, the parent or guardian is asked to fill out a questionnaire, followed by a short interview. Videos will be taken during both sessions and they are identified only by a code.

Please note that none of the tasks is a test of the child's personal intelligence or ability. The objective is to test the usability of the Augmented Reality systems.

Confidentiality

All data will be coded so that the child's anonymity will be protected in any research papers and presentations that result from this work. The participant's face will be blurred in any snapshot from the video included in the paper or presentation, in order to protect his/her identity.

Risk

Participants who have previously experienced photosensitive epilepsy are suggested to withdraw from the experiment due to the video game nature of the computer system.

Finding out about results

If interested, you can find out the result of the study by contacting the researcher, Ms Zhen Bai. She can be contacted in room SS06, Computer Laboratory, University of Cambridge, 15 JJ Thomson Avenue, Cambridge CB3 0FD. Her phone number is 01223763626 and her email address is zhen.bai@cl.cam.ac.uk

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Consent

Your signature below indicates that you have read and understood the information above about the experiment, confidentiality and risks and that you consent to the participation of the child. Participation is voluntary and you and your child can decide to withdraw from the study at any time with no penalty. This does not affect your legal rights. You will have received a copy of the consent form for your own records. If you have further questions related to this research, please contact the researcher.

____________________________ _______________________

Parent/Guardian of the Participant Date

____________________________ _______________________

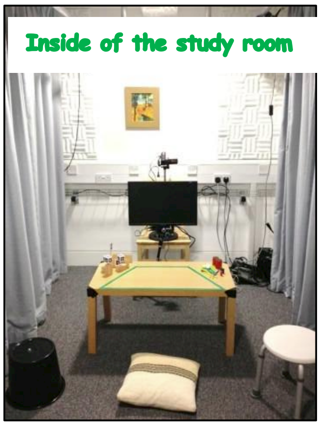
Researcher Date

University of Cambridge
Computer Laboratory
William Gates Building
15 JJ Thomson Avenue

Tel: +44 (0)1223 763626
Email: zhen.bai@cl.cam.ac.uk

- We are going to the **Computer Lab in Cambridge** to help **Zhen (Jane)** with her study

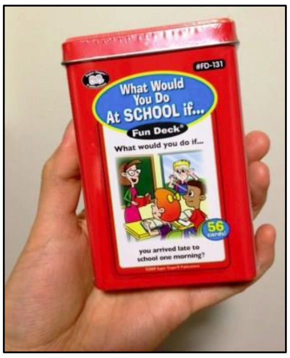
- What is the place like?



Zhen You Dad/Mom

- **Rewards** you will get after the study:

A gift



A certificate

Parent Questionnaire

Section 1: Participant Information

Name: ___________________ Age (month): _________ Gender: ☐ Male ☐ Female

Nursery/School status: ______________________________

Pretend play behaviour: ☐ Frequent ☐ Sometimes ☐ Seldom ☐ Never

Usage of computer: ☐ Daily ☐ At least once a week ☐ At least once a month ☐ Less than once a month

Please specify the computer device and applications that the participant uses:

Device: ☐ Desktop computer ☐ Laptop ☐ Touch screen device ☐ Others:__________________

Applications: ☐ Game ☐ Storytelling ☐ Education ☐ Others: ___________________________

Section 2: Evaluation of Play Engagement

[To be completed by the researcher] Theme Sequence:	1) _______ 2) _______ 3) _______
Condition Sequence:	1) _______ 2) _______

Session 1:

Please select the level of three aspects of play engagement below:

Cooperativeness or in-seat behaviour: ☐ Very Good ☐ Good ☐ OK ☐ Poor ☐ Very Poor

Interest or general attentiveness to the play things: ☐ Very High ☐ High ☐ OK ☐ Poor ☐ Very Poor

Happy smiling involved in play: ☐ Frequent ☐ Sometimes ☐ Seldom ☐ Never

Session 2:

Please select the level of three aspects of play engagement below:

Cooperativeness or in-seat behaviour: ☐ Very Good☐ Good ☐ OK ☐ Poor ☐ Very Poor

Interest or general attentiveness to the play things:☐ Very High ☐ High ☐ OK ☐ Poor ☐ Very Poor

Happy smiling involved in play: ☐ Frequent ☐ Sometimes ☐ Seldom ☐ Never

Section 3: Evaluation of the computer system

1. Which session do you think the participant enjoyed more?
   ☐ First session ☐ Second session ☐ Equal ☐ Not sure

2. In which session do you think the participant was more engaged?
   ☐ First session ☐ Second session ☐ Equal ☐ Not sure

3. Do you think the technology will help to promote pretend play for young children?
   ☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

4. Do you think the play themes (car, train and airplane) are appropriate?
   ☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

5. Can you name other play themes in the participant's daily play repertoire?
   ____

6. Anything you think could be improved for the computer program?
   ____
   ____

Child Questionnaire

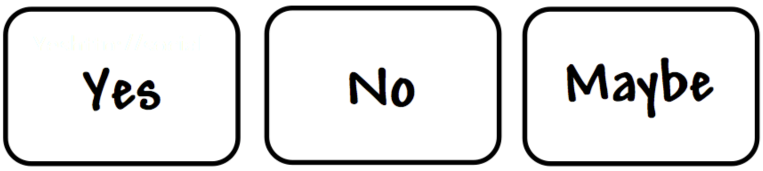
Case ID Number: ________________

Session non-AR:

1. Choose the face that shows how much you liked the play just now

Awful Not very good Good Really good Brilliant

2. Would you like to do it again?



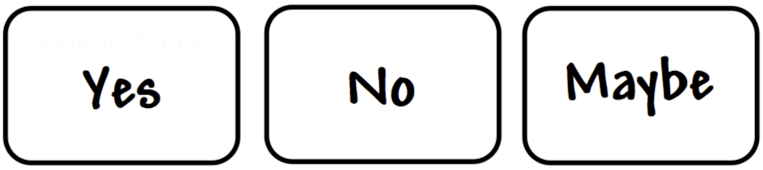
3. One thing you like about the play

4. One thing you don't like about the play

Session AR:

1. Choose the face that shows how much you liked the play just now

2. Would you like to do it again?



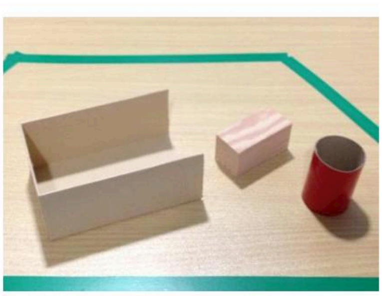
3. One thing you like about the play

4. One thing you don't like about the play

5. Are there other things you want to be on the screen?

Overall Questions:

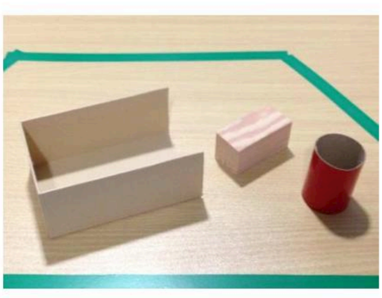
1. Which play is more fun?



without screen with screen

2. Why?

3. Which one do you prefer to play with your friend?



without screen with screen

Appendix C

Experiment Materials of the Chapter 6 Study

C.1 Consent Form

C.2 Parent Questionnaire

C.3 Teacher Questionnaire

C.4 Child Questionnaire

UNIVERSITY OF CAMBRIDGE
Computer Laboratory

Zhen Bai
PhD Student

Consent Form

Study Purpose & Procedure

The purpose of the study is to evaluate the effectiveness of an innovative computer system in promoting social pretend play of preschool-aged children in terms of symbolic thinking, communication and emotion expression. Two children will be observed playing in pairs with the computer system in two sessions on two separate days, and each session last no more than 30 minutes. At the beginning of the study, the researcher will show the children how to interact with the system. Then the researcher will ask the children to make a story together using the system. At the end of each session, the child will be asked some simple questions about his or her play experience. Videos will be taken during both sessions and they are identified only by a code. Please note that none of the tasks is a test of the child's intelligence or ability. The objective is to test the usability of the computer systems.

Confidentiality

All data will be coded so that the child's anonymity will be protected in any research papers and presentations that result from this work. The participant's face will be blurred in any snapshot from the video included in the paper or presentation, in order to protect his/her identity.

Finding out about results

If interested, you can find out the result of the study by contacting the researcher, Ms Zhen Bai. She can be contacted in room SS06, Computer Laboratory, University of Cambridge, 15 JJ Thomson Avenue, Cambridge CB3 0FD. Her phone number is 01223763626 and her email address is zhen.bai@cl.cam.ac.uk

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Consent

Your signature below indicates that you have read and understood the information above about the experiment, confidentiality and risks and that you consent to the participation of the child. Participation is voluntary and you and your child can decide to withdraw from the study at any time with no penalty. This does not affect your legal rights. You will have received a copy of the consent form for your own records. If you have further questions related to this research, please contact the researcher.

____________________________ ________________________

Parent/Guardian of the Participant Date

____________________________ ________________________

Researcher Date

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E-mail: zhen.bai@cl.cam.ac.uk
Webpage: http://www.cl.ac.uk/~zb223

Parent’s Questionnaire

Please provide the following information of your child:

1. Name:

2. Age (month):

3. Gender: ☐ Male ☐ Female

4. Has older sibling(s): ☐ Yes ☐ No

5. Has younger sibling(s): ☐ Yes ☐ No

6. Social pretend play (make-believe and role-play with other children):

   ☐ Frequent ☐ Often ☐ Sometimes ☐Seldom ☐ Never

7. Usage of computer: ☐ Daily ☐ At least once a week ☐ At least once a month

   ☐ Less than once a month

8. What computer device does your child use at home:

   ☐ Desktop computer ☐ Laptop ☐ Touch screen device (please specify: ___________)

   ☐Others: __________________

9. What does your child do with these devices:

   ☐ Game ☐ Education ☐ Storytelling ☐ Others: ___________________

Teacher Questionnaire

Teacher Name:

	Very good	Good	OK	Poor	Very poor
1. What do you think of the children' average engagement during the play?	☐	☐	☐	☐	☐
	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
2. Do you think the play themes are appropriate?	☐	☐	☐	☐	☐
3. Do you think the system could help guide children to plan a story in advance?	☐	☐	☐	☐	☐
4. Do you think the facial expression change feature can help children portray emotion of pretend character?	☐	☐	☐	☐	☐
5. Do you think the computer system could help encourage social pretend play for children?	☐	☐	☐	☐	☐
6. Do you think it would be beneficial to use the system in the classroom?	☐	☐	☐	☐	☐

Group 1 No Face Day 2

P1 Name: ________________

1. Choose the face that shows how much you liked the play just now

Awful Not very good Good Really good Brilliant

2. Things you like about the computer?

3. Things you don't like about the computer?

Group 1 Face Day 3

P1 Name: ________________

1. Choose the face that shows how much you liked the play just now

Awful　Not very good　Good　Really good　Brilliant

2. Things you like about the computer?

3. Things you don't like about the computer?

4. Which play do you think is more fun?

(a) no face change

(b) face change

5. Why?

6. Are there other things you want to be on the screen?

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