CHILDREN ADAPT DRAWING ACTIONS TO THEIR OWN MOTOR VARIABILITY AND TO THE MOTIVATIONAL CONTEXT FOR ACTION

by

SITI ROHKMAH MOHD SHUKRI

A thesis submitted to
The University of Birmingham
for the degree of
DOCTOR OF PHILOSOPHY

School of Computer Science
College of Engineering and Physical Sciences
The University of Birmingham
September 2016

Abstract

Past work on children's drawing from the "process oriented" approach focused more on *how* children draw without considering *what* and *why* they draw. Both *what* and *why* under the "product oriented" approach need to complement the question of *how* in order to understand children's drawing behaviour better. The work of this thesis focuses on the"process oriented" approach that deals with the motor process of children's drawing without neglecting the importance of the "product oriented" approach.

This thesis seeks a better understanding on psychological processes involved in drawing and drawing development in children to study their drawing behaviour. This is why the thesis is reviewed under the theoretical framework of Adaptive Interaction. This framework (Chapter 2: Background and Theoretical Framework) studies children's drawing through a utility maximization approach that derives its explanatory power from three components of human behaviour; *ecology*, *utility* and information processing *mechanisms*. As such, it raises the following questions: (1) "How would children draw on a tablet given that they have cognitive and motor limitations?"; (2) "Why would children draw on a tablet given that there are limitations on tablet and drawing software?" The framework helps to provide an explanatory and predictive account of children's adaptation of drawing strategies on a tablet. The empirical work of the framework is conducted to answer the following research questions: (1) "How do children adapt their drawing strategies according to their own motor variability and to the limitations of tablet and drawing application?"; (2) "How do a child adapt to the drawing actions according to his/her own motor variability?"; and (3) "Does adaptation to motor variability explain age-related changes in drawing performance?";

To answer these questions, I conducted empirical studies (Chapter 3 to 6) to examine how children adapt their drawing actions to their own motor variability and to extrinsic motivations (rewards). My study consisted of drawing tasks that tested the model of

movement planning based on the Statistical Decision Theory. The idea was to see how children act as ideal drawing planners when choosing movement trajectories on touch surfaces. I derived predictions of the hypothesis from children's drawing on a touch screen with regions carrying reward and penalties. When a penalty region is placed near to a target region, adults are known to alter their motor plan. In particular, they shift their aim point to avoid the penalty region. The model predicts shifts in subjects aim point in response to changes of reward and penalty structures within the drawing environment. The result of my studies show that children make near optimal adaptation to subjective rewards, their own cognitive and motor limitations and to the limitations of tablet and tablets drawing software. The work reported here shows that a child's strategies for drawing on a tablet can be understood as a Bayesian adaptation to movement variability, motivation and limitations of the device surface. This perspective may offer a promising mean of understanding children's drawing strategies.

At the end of the thesis, I hope to be able to articulate that interaction is adaptive because it is driven by strategies that are constrained by these three components of *utility*, *ecology* and *mechanism*. Weaknesses in any one of the components contributing to the psychological components of the drawing can have far-reaching effects. The work of this thesis, therefore is discussed and summarized according to the empirical and theoretical perspectives of children's drawing.

ACKNOWLEDGEMENTS

This thesis I dedicated to ..

My lovely husband, *Shamsulnizam Zaulkipli*, who has been my strongest support throughout this journey. "*By the Mercy of Allah, I wouldn't have done without you Sayang.. May Allah reward you abundantly in this dunia and akirah..*"

My two adorable children, *Ahmad Zhafran* and *Balqis Hannani*, for putting colours to this monotone journey. "*Ibu loves you..*"

My beloved *mak* and *ayah*, *Khadijah Zakaria* and *Dr. Shukri Abdullah*, for raising me to dare to be different. "*This journey is for both of you..mak ..ayah..*"

My forever caring *Kak*, *Siti Nabilah Shukri* and her happy kids always, *Saalih*, *Sufyan* and *Safiyyah*. "*I will forever remember my time in London with you especially Summer 2016, when this thesis was written..*"

My special thanks also goes to *Nurul Husna*, my younger sister who has been together in this journey while she completed her study, to my family and in-laws family, all my friends in the UK and Malaysia and most importantly to all the parents who had allowed me to have their lovely children as my study participants. These studies would not have completed without their interests and commitments. I wish I could name more of you here who have been there for me, you will forever resides in my heart. May *Allah* repay kindness to every one of you.

Thank you to *Islamic Development Bank Jeddah* for sponsoring my study, *Universiti Teknologi PETRONAS* for the study leave and support given and *Greenlane Masjid* for the spiritual journey back to faith.

Last but not least, to my supervisor *Andrew Howes*, all your throwing critics and arguments had made me the researcher that I am today. With that, I am truely grateful. Thank you.

CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Drawing is one of the most common activities that children enjoy. It is also a task that becomes a platform for adult to understand children better. This is the reason why drawing has long captured the attention of parents, teachers and child development researchers where they try to understand the *what*, *why* and *how* children draw. To answer these questions, drawing in the literature review has been studied from two different perspectives, which are; within a "product oriented" approach, dealing with the *what* and *why* of drawing and; "process oriented" approach, dealing with the *how* of drawing (Vinter, 1999).

The "product oriented" approach is related to the cognitive aspect of children's drawing. It accounts for the utility function that gives motivational factor for children to draw. The approach investigates the marks left on paper that form a representational meaning of an object (e.g., airplane) or non-object (e.g., motions, sounds and feelings) on the final product. It is regarded as children's perception, communication and manipulation acts. In terms of perception, drawing is used as a medium to understand children's thoughts and ideas (Brooks, 2009; Hamama & Ronen, 2009); and their inner feelings and emotions (Thomas & Gray, 1992; Thomas & Jolley, 1998; Hamama & Ronen, 2009). As for communication, drawing is used for social context and as a problem solving tool (Anning, 2000; MacDonald & Gustafson, 2004; Haney et al., 2004; Xu et al., 2009); and to promote learning (Adams, 2002; Anning, 1997). Drawing as manipulation on the other hand, is used for clinical or assessment approach such as Draw-a-Person-Test, House-Tree-Person-Test or Kinetic-Family-Drawing-Test (Thomas & Jolley, 1998); and to examine children's cognitive and developmental growth (Goodnow, 1978; Lange-Küttner et al., 2002; Picard & Gauthier, 2012). The drawing product in this approach is viewed according to children's visual (what they see) or intellectual realism (what they know). Visual realism occurs when a child looks at an object in the real world and presents it graphically, known as view-based depiction. Intellectual realism occurs when the object drawn is based from memory, known as object-based depiction. Therefore, based on this approach, *what* explains the content of the drawing that children are interested to draw. It is the ecology task of the drawing that is described more in the background literature of section 2.3. This final product of drawing is interpreted by the cognitive aspect of children's mind and is driven by intrinsic motivation that explains *why* they draw.

The "process oriented" approach is related to the motor aspect of children's drawing. The approach is based on the organization of strokes and movements used in drawing that involves perceptual motor skills. It looks at the children's movement strategies and actions while drawing. In this context, the action of drawing is studied in terms of (1) relation between movement parameters (e.g. speed, curvature, direction) and (2) how these relations change with age (Pellizzer & Zesiger, 2009)). Therefore, drawing is mostly understood as a behavioural aspect in movement sequencing and kinematic (J. Laszlo & Bairstow, 1983; Adi-Japha et al., 1998; Viviani & Schneider, 1991); motor and drawing plan (Nihei, 1983; J. I. Laszlo & Broderick, 1985; Vinter & Mounoud, 1991; Meulenbroek & Thomassen, 1993; Vinter, 1994); and motor and developmental growth (Rueckriegel et al., 2008). The approach considers how children draw from the perspective of children's motor control especially in their motor planning of kinaesthetic movement.

Children's drawing has been reviewed from a variety of drawing aspects, at both low-level (e.g., stroke preferences) and high-level (e.g., perspective mapping) drawing tasks. The different capacities in cognitive and perceptual motor control from different age groups among children and adult has also been reflected on the literature review of drawing on paper. As such, drawing can be understood as a continuous process of developmental progress involving both cognitive and motor control that improves with age. Therefore, both "product oriented" and "process oriented" approaches need to be studied side by side in order to understand children better. Drawing studies as "process oriented" approach should also consider both the *what* and *why* questions from "product oriented" approach in order to answer the *how* of when children perform the task. Inadvertently, evidence from literature work has shown that this is not always the case. When it comes to drawing, child development researchers tend to look into one aspect or another distinctively without much consideration on both factors together. For example, often work under "process oriented" approach, such as movement sequencing and kinematic did not consider the ecology of task that account to the utility function of children's drawing (e.g., Pellizzer & Zesiger, 2009). For example, children were required to draw strokes following a patterned path such as curvature strokes that form a non-representational drawing. The purpose of the task was to find out *how* children draw curvature strokes to compensate between curvature path and speed while drawing. However, it is lacking the motivational context for children to complete the task. Instead of asking children to draw what they naturally like to, they would have to draw according to what the instructor asked for. Perhaps if the task was designed to be more engaging or interesting for them, children may use different strategies to complete the task. This is what is most lacking in children's drawing task especially when it is used to study their movement control in drawing. It did not take much or at all into account the utility functioning of the task to children. This should be addressed.

Apart from drawing on paper, children these days make increasing use of tablets for entertainment, learning activities and this includes for drawing. In order to do so, they need to learn to use their finger tips apart from pen stylus, for activities, such as drawing, that would otherwise require the use of a tool such as crayon or pencil. The learning required can be challenging. Recent works have shown that while children seem to like using tablets, they have specific difficulties. For example, children have difficulty maintaining contact with the screen. They also have a tendency to miss a greater proportion of onscreen targets compared to adults when only single touch action is required (Anthony et al., 2012; Brown & Anthony, 2012) and they make unintentional touches with trailing fingers and thumbs (McKnight & Fitton, 2010). The problems could possibly be due to their smaller fingers, less fine motor control and less experience with technology (Anthony et al., 2012). Nevertheless, drawing is still a task that may increasingly be done by children on a tablet. Despite the fact that many children choose to draw on a tablet, there have been few studies on how they do so. While drawing on a paper seems like a natural task for children, how easy is it for them to draw on a touch screen device? More specifically, how do children adapt the way they draw to the device and to their own limitations? This is what the thesis is about.

Current research suggests that children's drawings on a touch screen or a computer convey far quicker and richer information than had often been claimed in the past (e.g., Helbig & Ernst, 2007; McKnight & Fitton, 2010; Zhai et al., 2012). Although drawing using these mediums could yield similar result to drawing on paper, traces and marks left on screen could be quantified more accurately giving a theoretical and empirical understanding on children's motor process (e.g., Lin et al., 2015; Tu et al., 2015) and drawing strategies (e.g., Tabatabaey-Mashadi et al., 2013; S. Price et al., 2015). The very act of drawing itself would not only involve sensorimotor coordination to perceptual graphic production in cognitive and motor aspects, but also adaptation of interaction to the medium of representation. There were less work that investigates human adaptation to interactive technology especially among children. Most work that study on children's motor skill look into reaching and pointing task. This is because pointing constitutes the basic act of hand movement. Such movement merits a careful scrutiny as it contributes to other complex physical skills such as drawing. Since the act of drawing is part of a goal-directed motor behaviour, it is in these pointing and reaching tasks that I am interested to look into.

The basic act of pointing is one of the most common human motor behaviours that was highlighted in the motor development literature. The task is about the production of accurate rapid aimed movements toward a target. Fitt's law ideally study this simple aimed movement of pointing task. It was used to compare how children and adults acquire targets using mice or other pointing devices (Jones, 1991; Hourcade et al., 2004; Donker & Reitsma, 2007) to investigate their hand task motor performance (Lambert & Bard, 2005). However, when aiming towards a target, Fitt's law did not consider task difficulty but rather counter balances between target distance and target width (Guiard, 2009). The amplitude movement is mostly compensated by either increasing the aiming time or by becoming less accurate. This is beneficial at the level of motor planning but not at the corrections of ongoing movements (Bertucco et al., 2013). What if when reaching a target, there are other obstacles? Let say a person tries to reach a cup of coffee to drink but there is a small bottle of sugar in the middle of the way that hinders the path of the hand movement. The person may need to adjust the speed of their hand movement in reaching the target well by trying to avoid the obstacle. These external constraints need to be also considered when studying motor behaviour. Nonetheless, Fitt's law does not take into account extrinsic cost in determinant to motor behaviour. As such, Fitt's law may not be suitable to attain the best hand movement performance in a complex environment. Bayesian Decision Theory however do caters these additional constraints in movement planning. Therefore, the work in this thesis are grounded in Bayesian Decision Theory.

Bayesian Decision Theory has previously been successfully applied to explaining how people adapt pointing to their own internal noise (Trommershäuser et al., 2003b, 2005, 2006; Wu et al., 2006; Maloney & Zhang, 2010; Hudson et al., 2012). Literature work have shown that adult's performance in aim pointing are optimal. However, the approach has not been applied in the context of children's work. Why is it important to know whether children can make better adaptation when it comes to movement planning? As decision theory can apply to conditions of certainty or uncertainty and risk, the idea can be used to understand how children adapt strategies to the risks and perceived costs of drawing errors, slips and mistakes. The uncertainties gathered from constrained environment when using a physical device with movement interaction coupled with children's less stabled motor skills in the motor system, originates the motor noise that can lead to variable motor output. The best way to know whether children would be able to overcome such challenges in a rapid movement task is to study their adaptation to such environment. Therefore, Bayesian inference can be used to model adaptation of the motor system to persistent changes in the movement planner's environment. When an obstacle is placed into a goal-directed movement, adults are known to select the most efficient strategies by compensating challenges to the reward of the task. Would children be also able to choose a good motor strategies to maximize their expected gain? By looking into the context of adaptation, we can understand children's motor behaviour better on how they perceive such challenges arises in any given interaction.

The next section describes the summary of the goal and work of this thesis together with the challenges that need to be overcome along the way.

1.1 Overview of the thesis

Past work on children's drawing from the "process oriented" approach focuses more on how children draw. They made less account on *what* and *why* children draw to study *how* they draw based on the motor process. These basic questions of *what* and *why* are essential to shape *how* children naturally react or respond to drawing task. In any given task, there should also be emphasize on what account as utility to children when performing the task. The questions of *what* and *why* need complement the question of *how* in any given task to understand children's drawing behaviour better. The focus of this thesis lies under the "process oriented" approach that deals with *how* children draw on a tablet. However, both *what* and *why* are accounted together in the drawing task, as the utility function to motivate children to draw better. This utility function can also be related to the reward function of the drawing task which serves as the motivational context of action for children to draw better and longer.

This is the reason why the work in this thesis studies children's drawing under the theoretical framework of Adaptive Interaction. Adaptive Interaction framework is used to understand human interaction with technology through a utility maximization approach. Therefore, this framework helps to investigate how children draw on a tablet from a theoretical and empirical perspective through a utility or reward function. The framework raises the following questions: (1) "How would children draw on a tablet given that they have cognitive and motor limitations?" and secondly: (2) "Why would children draw on a tablet given that there are limitations to tablet and drawing software?". The work focuses mainly on perceptual and motor skills of children's drawing on a tablet, looking closely at pointing tasks that are often done in the context of drawing. To understand how children make their drawing movement, the work follows the model of movement planning that is grounded in Bayesian decision theory. Bayesian decision theory also provides one key approach to understanding adaptive behaviour given cognitive and experiential constraints (Payne & Howes, 2013). It is possible that a child's strategy for drawing on a tablet could be understood as a Bayesian adaptation to movement variability, motivation and limitations of the device surface.

However, other challenges arise when it comes to tablet and drawing software. These challenges revolve around a design issue; the software tool and the drawing task must suit both younger and older children. Children show a large variety of discrepancies in the growth development according to their own cognitive and motor abilities. Therefore, the task needs to suit these differences and at the same time still be engaging for children to draw. This would be very challenging. The overall design requires careful thought that it should be challenging enough for older child users but still conveniently cater towards the limitations of younger child users. The challenges can be divided into three aspects which are: (1) the context of the drawing task itself; (2) the interaction within a single task and the overall flow; (3) the utility function of the task that is the drawing feedback and reward. A good design would be able to help answer the research questions from empirical work perspective. These research questions are addressed in the next chapter 2 of Background and Theoretical Framework.

In what follows, Chapter 2: Background and Theoretical Framework explains the literature review in theoretical framework perspective. This chapter explains about children's drawing in terms of three components (*utility*, *ecology* and *mechanism*) of the framework. The fourth component, *strategy space* describes the approach used for the empirical work of the thesis, which to answer the main research questions addressed at the end of the chapter.

Chapter 3: Drawing and utility (Study 1) explains the first experimental work of the thesis that emphasized on the utility function of the drawing task. This chapter addresses about the utility function to be set in the design of the drawing task. The purpose of this chapter is to highlight about the motivational context for children's action on drawing. The experimental work in this chapter explores children's drawing behaviour towards the reward conditions set and to find out whether children are adaptive.

Chapter 4: Drawing and movement planning (Study 2) introduced the second experimental work that used the model of movement planning of Bayesian approach. The experimental work in this chapter used the approach to examine whether children adapt optimally in their drawing strategies. The design of the task took into account all three components of the framework (*utility*, *ecology* and *mechanism*). The fourth component (*strategy space*) is the approach used for the analysis of the empirical work. However, a limitation is realized in terms of the *ecology* of the task. Therefore, another study is required in order to overcome the limitation.

Chapter 5: Drawing and calibration process (Study 3) explains the adaptive method of visuo motor calibration that is used to find the right target size in the initial phase of the experiment. The procedure used in the calibration is a Psychometric function of Cumulative Gaussian. This method helps to strengthen and overcome the limitation and weakness of Study 2. However the modification to the ecology of the task has given an effect towards children's response to the task. Children were found less interest to pursue the task. This means the utility function of the task need to be strengtened. A new study is required to replicate the experiment.

Chapter 6: Drawing and stroke attributes (Study 4) closes the experimental phases of the thesis. The design has been established in all aspects of the theoretical framework components. The utility function of the task in this study was strenghtened to overcome the limitations of Study 3. This chapter also explore on stroke attributes in children's drawing that are not included in the earlier experiments. This chapter is able to answer all main research questions of the thesis and gives an insight about stroke making.

Chapter 7: General Discussion discusses and concludes all experimental findings of the thesis. This chapter connects each experimental work and design of the drawing tasks to the theoretical framework, answers the main research questions and the thesis goal as discussed in Chapter 1 and 2. At the end, the chapter raises up some opportunities for future work in children's drawing.

CHAPTER 2

BACKGROUND AND THEORETICAL FRAMEWORK

2.1 Introduction

This chapter reviews the background literature from the perspective of a meticulous theoretical framework. The theoretical framework help to explain the work in the thesis of how children adapt their drawing strategies when drawing on a tablet. The framework, Adaptive Interaction by Payne & Howes (2013) is designed to underpin the bounded nature of human behavior and to reason about how and why people interact as they do. It is a utility maximization approach to understand human interaction with technology. By using this framework, the thesis seeks a better understanding of psychological processes involved in drawing and drawing development. It helps to provide an explanatory and predictive account children's adaptation of drawing strategies on a tablet.

The framework (Figure 2.1) derives its explanatory power from three components of human behavior, which are *ecology*, *utility* and information processing *mechanisms*. *Ecology* concerns what is experienced by an individual and the constraints occurred during interaction in an environment. *Utility* concerns what an individual finds value on pursuing the task. *Mechanism* concerns the cognitive capacities that process information. These three components shaped the fourth component that is the *strategy space* to explain human behaviour. The strategy space predicts the action of the individual that adapts to the task through a utility maximization of all the three components.

This framework shapes the question:- (1) "How would children draw on a tablet given that they have cognitive and motor limitations?" and; (2) "Why would children draw on a tablet given that there are limitations of tablet and tablet software?". In the first question, children's cognitive and motor limitations are derived from the information processing mechanisms that drive the motor system. This is related to the *mechanism* component of the framework. The second question, "why would children draw?" is derived from the motivational context of *utility* component of the framework. The limitations imposed by tablet and tablet software in this question is related to the *ecology* component of the framework which is about statistic property concerning motor control. The combination of these three components is necessary for an individual to select an appropriate action that is adapted to the task, which helps to answer the first question on "how". In the empirical work, the strategy space requires a computational approach to inspect whether a person is adapted to the task optimally. Therefore, this chapter introduced the framework with illustrated examples of drawings and perceptual-motor tasks in relation to the work of this thesis. This is embedded as part of the background literature of children's drawing.

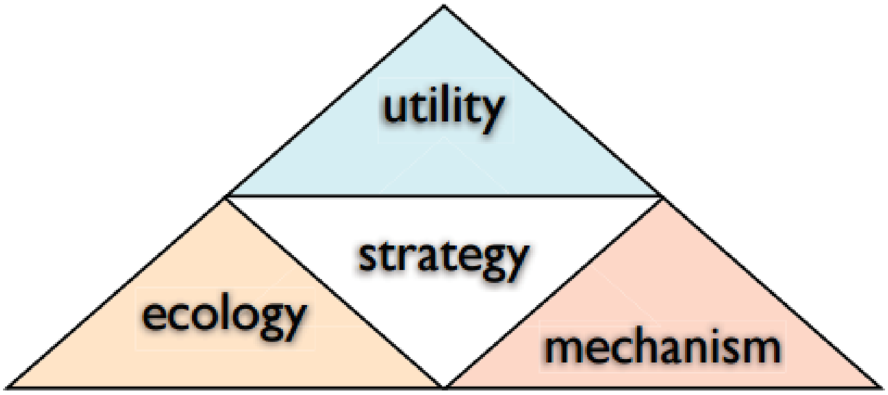


Figure 2.1: An illustration of the Adaptive Interaction framework. The first three components (utility, ecology, mechanism) shape the fourth: the choice of strategies which are discretionary methods for achieving useful behaviour. In the absence of any one of the first three components, the strategy space is unbounded. Source from Payne & Howes (2013).

2.2 Utility

Why do children like to draw? What accounts as utility to the children in drawing? One of the reasons that were proposed by theories was, children draw because they regard drawing as a form of play. They are engaged in drawing and become absorbed in it as much as they do when playing with other toys. Their natural need to develop a mastery of play is exhibited the same way to mastery in drawing. This can be reflected from the satisfaction of drawing activity itself that is accounted as play, and they share the same characteristics qualities including aesthetics, imagination, fantasy, reality and innovation and providing opportunities for experimentation and creativity (Mayles, 1989; Wood &

Hall, 2011). Drawing is a distinctive play activity that transform from what is absent in a piece of paper to something that is symbolic to the drawer (Wood & Hall, 2011). Drawing as a play activity in summary, is considered to be particularly effective in many forms towards a quality characteristics (Anning & Ring, 2004; Carruthers & Worthington, 2011) that may lead to other reasons such as for communication or self-expression in drawing.

Children begin drawing to express their thoughts and emotions that cannot be easily put into words (Ives, 1984; Winston et al., 1995; Jolley et al., 2004). Children's view, expressions and communications through drawing provide a psychological perspective of children's cognitive development which dominates the children's drawing literature (Goodnow, 1978; Punch, 2002; Veale, 2005; Einarsdottir et al., 2009; Brooks, 2009). Drawing has been proposed to have various roles in the assessment of children opinions and experiences (Goodenough, 1926). Through symbolic expression, children have control over drawing to construct their thinking (Anning, 1997). Drawing also has the potential to play a role in the visualization and development of children's ideas where they use to develop and store concepts from what they perceived around them.

Many authors also suggested that a major reason why children draw is to make graphical representations; that is to say, to make pictures. Children draw because they find it satisfying to produce pictures. In terms of aesthetic quality, the patterns of marks in drawings for example is suggested to be perceptually satisfying to children (Kellogg, 1970). Arnheim (1954) proposed that the notion of visual balance in composing a picture is naturally satisfying. (Kellogg, 1970) has also claimed that the basic forms such as circles and rectangles that are constructed from children's drawing are intrinsically attractive. Although these aesthetic principles have yet to be established within the context of children intrinsic motivation, the progression from meaningless, abstract scribbles to meaningful and detailed representations could be the reason, why picture making is rewarding to children (Matthews, 2003). Apart from picture making, the use of graphic symbols has also provide greater satisfaction for children to artistically expressed their visual and emotional experiences to others (Arnheim, 1954; Kellogg, 1970; Lowenfeld, n.d.; Gardner, 1980; Selfe, 1983). In particular, picture making symbolizes and expresses their thoughts, feelings, interests and experiences. By drawing too, children are able to use their skills and knowledge to represent their own way of making a mark.

Although the primary motivation for children to draw seems to intrinsically come from the drawing activity itself, the external social impact should also be considered as one of the reasons for children's drawing. There are two ways of how drawing as a social or cultural resource could influence children to draw. The first, through drawing resources and materials be made available by parents and teachers at home and school (Morrow &

Rand, 1991; Anning & Edwards, 2006). Adults encourage children to draw as a regular art activity, not only by providing them with various materials but also by showing them examples of how to draw. Thus, drawing would then naturally become part of children's daily activities (Anning & Ring, 2004). In school, other than using drawing as an art time filler, drawing is also used as a tool for design (Hope, 2000) and research work (e.g. Adams, 2002; Haney et al., 2004). Secondly, when adults provide drawing feedback to children individually (Braswell & Callanan, 2003) or in the company of peers (Richards et al., 2003), children enjoy when other people show interest in their drawings. This interest could be in the form of praising, giving feedback or reward to the pictures drawn. Children become encouraged to draw more for these purposes. Therefore, social context is also regarded as one of the motivational factors to why children like to draw.

There are many other reasons to what makes children find value in drawing. This utility differs from one child to another. While utility in drawing is regarded as a function of motivational context, Trommershäuser et al. (2008b) treat utility as a measurement of psychological process in their work. That is to say, utility is the performance measurement of the task where the action of the task is driven by a motivational context, information process and the difficulty of performing the task. Beyond drawing, utility is a theoretical construct in the work of a motor control or manual control even of the hand. What children find as value in drawing is also influenced by the task ecology which is the task distribution itself; and the mind mechanism which processes the information necessary in order to draw. Therefore, the utility function in the framework is used to measure the optimal outcome of an individual task. In Trommershäuser et al. (2003a) work, subjects were able to optimally plan their movement when they have full information about the stimulus configuration of the task and the reward assigned to it prior to movement onset. This thesis follows their work in investigating children's drawing of cognitive task. The utility function of the drawing task is further discussed and investigated in Chapter 3 of Study 1.

2.3 Ecology

This section briefly describes children's common drawing tasks in the literature. Van Sommers (1984) stated that children at an early age start to use scribbles of purposeless marks and then move to strokes to show purposeful marks. The vast majority of the strokes are simple lines, arcs, circles and dots. When they reach the end of their second year, children start to experiment with shape, contour and visual properties to portray information

Figure 2.2: How I spend my weekend (5 years old)

in their drawing (Wolf & Perry, 1988; Einarsdottir et al., 2009). Among the commonly drawn pictures by children at an early age that are expressively drawn are trees and houses (see Carothers & Gardner, 1979; Winston et al., 1995). Arnheim (1954); Maitin et al. (1968) agree that other popular topics of children's representational drawings are cars, boats, planes, animals and flowers. Several researchers have found that young childrens drawings of human figures, dogs, trains, planes, suns and stars are not depicting any particular object but a generic type, a prototype (Tallandini & Valentini, 1991; Milbrath, 1998). Thus, children choose simple patterns such as circle, diagonal cross and different line orientations as the basic elements in their drawings (Milbrath, 1998). Often, they use continuous lines to construct small figures then large figures. These drawings are basically in their canonical orientations.

The most popular topic, however has always been the human figure (e.g., Koppitz, 1968; Thompson & Golomb, 1992; Zhi et al., 1997; Picard et al., 2007). It has been widely reported that when young children are asked to draw a human figure, they would start with a tadpole figure with legs rather than arms. As they develop, the human figure would have a trunk as the body, sometimes without the arms, or arms inappropriately placed at the side of the head. There are many studies in the literature that reported what children from different age group choose to draw as human figure.

In drawing literature, elements such as depth representation and perspective projection are among the tasks that are given to children to see how they would draw. In representing depth, for example, if there are two objects on a table placed one behind another, how would children portray depth information in their drawing? Previous studies have shown that children between the age of 5 to 6 years old would draw the objects side by side whereas children starting at age 7 would draw the object on top of the other object in vertical order (N. Freeman et al., 1977; P. H. Light & MacIntosh, 1980; P. H. Light & Humphreys, 1981; Davis, 1983; Ingram & Butterworth, 1989). After they are 8 years old, children would start to use masking or partial occluding approach similar to adult's drawing when representing depth. It is suggested that children below 8 years old use more transparency in the occlusion or separating the objects side by side because their actions are based on intellectual realism (what they know) rather than view specific (what they see) (N. Freeman et al., 1977). While M. Cox (1981) believes that children choose to represent the objects as a whole scene rather than using partial occlusion. However P. Light & Simmons (1983) concluded children may have limitations in utilizing occlusion as a graphic skill. Although, Davis (1983) concludes that children are still concerned to include as much information as possible regarding the array presented in their drawings.

Nonetheless, there is a discrepancy about children's initial intention of what they choose to represent and what the final drawing can be said to represent (Luquet & Costall, 2001; N. H. Freeman, 1972). Luquet & Costall (2001) discussed mainly on the aspect of *visual realism* and *intellectual realism* that distinguish between 'children draw what they know' rather than 'children draw what they see'. Their work articulates to the questions of why and what children choose to draw given a task. This raises the question of mechanism to dealing with discrepancies in the realization of intentions in developmental drawing. This question is discussed in the next section.

2.4 Mechanism

According to Van Sommers (1995), drawing is a complex system of psychological processes that involves motor output, imagery, memory, meaning, perception and aesthetic. These components of psychological processes can be derived from the mechanism of children's mind, concerning the information processing system implicit in the human brain that determines what a person can do. For example, children as early as in their second or third years of age could produce drawings related to symbolic actions on paper (Gardner & Wolf, 1987). This suggests that by this age, children are already aware of the function of graphic symbols to represent objects in real world. By the age of three to four years, they are able to draw full representational drawings on paper recognizable to others

(Copple & Gardner, 1981; Krampen, 1991; Thompson & Golomb, 1992). This is soon followed by their being able to mimic the conventional way of adult's drawing. This shows that drawing performance is affected by the childrens developmental growth with age. How do we know that developmental progression has to do with mechanisms rather than strategies?

Studies have shown that drawing first started with scribbling (Kellogg, 1959; N. H. Freeman, 1972; Gardner, 1980; S. Cox, 2009) which make their first mark of actions (Lukens, 1896; Matthews, 1984). According to Adi-Japha et al. (1998), scribbling in the initial phase, is determined mainly by the mechanical function of wrist, arm and hand of the motor system without guidance of visual planning. Children then move to drawing of shapes or contours that represent visual properties (Wolf & Perry, 1988). During this early phase, the scribbles become complex patterns that are guided by visual planning and increment of perceptual and motor coordination which are balanced by the aesthetic qualities based on their imagination or memory (Arnheim, 1954; N. H. Freeman, 1980; Cherney et al., 2006). These examples of graphic symbols are characterized by the size, position and orientation of marks that represent actions to give meaning to drawing (e.g., emotion, speech or characteristic motion) (Einarsdottir et al., 2009). Theoretically, the components of the drawing system suggested by Van Sommers (1995) may differ in younger and older children in terms of mechanism. According to Toomela (2002), in the early stages of drawing development, the drawing process is less demanding with respect to motor performance in younger children as they pay less attention to the details of their drawing. When details become important at a later stage, fine-motor skills become significant, thus affecting the drawing measures of older children. These findings suggest that the development from immature to mature drawings are based on the mechanism of the psychological systems. This could be the reason why drawing behaviour appears less flexible in younger children at the age of 7 to 8 years old than older children at 10 years old (Karmiloff-Smith, 1990; Zhi et al., 1997). The next paragraphs show examples of developmental progress in children's drawing.

In Jolley et al. (2004) work, children from 4 to 12 years old were asked to draw a happy and a sad expressive drawing. These drawings are assessed individually and the quantity and quality of mood expressed in the drawings are found to have increased according to age. When children were asked to label emotions in the drawings, younger children were able to differentiate between happy and sad emotions but they find it difficult to distinguish more complex emotions (e.g. anger, fear or disgust) than older children (Brechet et al., 2009). It seems that younger children look for graphic representation rather than details in the drawing. Meanwhile Karmiloff-Smith (1990) reported that younger children's drawing are more data-driven than theory-driven. These examples can be related to the imagery, memory and/or meaning components of a drawing system.

On perceptual motor aspect, previous studies have shown that children of 5 to 6 years old have difficulty in drawing oblique lines (Goldstein & Wicklund, 1973; Berman et al., 1974) to form diamond shape unless given explicit visual guidelines (J. Laszlo & Bairstow, 1983; Broderick & Laszlo, 1987). It was also shown that 5 and 6 years old could not accurately copy other simple figures due to the lack in their perceptual and motor abilities (J. I. Laszlo & Broderick, 1985). This could probably be due to the way they plan their drawings. In a task of copying geometrical figure, Vinter (1994) found that young children of 4 to 5 years old plan their drawing movement by drawing from segment to segment without considering the entire sequence of the figure level. Children from 6 to 8 years old on the other hand, appear to plan their drawing movement at the figure level as they tend to make continuous unsegmented drawing which is called as threading. Threading starts to appear in childrens drawing as early as when they are 5 to 6 years old, then it is dominant in the movement sequence of their drawing at around 6 to 7 years old, but it is used less after they are 8 years old (Ninio & Lieblich, 1976; Nihei, 1983; Vinter, 1994). Planning in drawings made by older children after 8 years old, resembles those of adults, which uses the combination of segment and figure level in their drawings. While these explain the relation of developmental progress to the children's mechanism at different ages, the next question is, does adaptive capacity develop in children's drawing?

Let's consider how children would draw a triangle. This may be an easy task for adults as they probably use a single accurate stroke to complete the triangle since they have less variable hand movement. Children in contrast, may require some particular strategy adaptation. The triangle might be drawn in a single stroke with slow but accurate movement or drawn faster but with multiple-strokes to complete it; such as leaving one part of the triangle corner open and adjust to close it later with another stroke. This is one example of how children might adapt in drawing actions. According to Brown & Anthony (2012) and Anthony et al. (2012), children use more strokes than adults when drawing simple shapes. For example, to draw a rectangle, adults often draw the four sides with a single stroke, whereas children might use four separate strokes. This drawing strategy might be an adaptation to the fact that children's fine motor skills are less developed. However, the strategy has a negative consequence as greater care is required to align the start point of one stroke with the end point of the previous stroke. Young children are known that they tend to be locked into an established drawing strategy even if new information of an object to be drawn is given. They adapt by elaborating detail to the picture drawn rather than adjusting their basic strategies (Van Sommers, 1984).

McWhinnie (1971) reported that 90 percent of the drawings changed substantially when children were introduced new drawing strategies. This shows that while adaptation seems to be a natural course to children, they would still require visual guidance for adaptive capacity to develop in drawing.

2.5 Strategy

This section explains strategy, the fourth component of space strategy in the framework that hinges on the idea, illustrated in Figure 2.1, that all three components are required to predict the strategies that people will adapt in order to perform selected tasks. The space strategy is used to find the best approach to provide a predictive, cumulative and explanatory account of adaptation of how an individual plan and organize its decision to perform the selected task. The space strategy is delineated by the ecology of the task that is the experience of the individual towards the task, motivated by their internal subjective utility function and driven by the cognitive mechanisms that allow them to process information. This section describes the model approach used to study the behaviour that emerged as an adaptation to the combination of utility, ecological experience and information processing bounds. As the focal issue of this section is to explain the method used to examine how an individual makes drawing movement and the motor aspect of hand movement, the perceptual motor processes is described and a strategic approach of drawing actions is justified within this developmental theoretical framework.

2.5.1 Perceptual Motor Strategy

Our daily interaction with the world either with people or physical environment almost certainly involves movements. These movements become the mediated interaction with the world via the motor system. All actions from a simple task such as picking up a pen from the floor to complicated task such as swimming requires movements that are generated through motor commands. Since drawing constitutes movement of hand motor control, this thesis refers to the basic act of pointing as the common ground of understanding human motor behaviour. The pointing movement in the motor literature is about the production of accurate rapid aimed movements using finger or mouse position from an initial position to a target. Fitt's law ideally study this simple movement of aimed pointing task. Prior studies have used Fitt's law to compare how children and adults acquire targets using mice or other pointing devices (Jones, 1991; Hourcade et al., 2004;

Donker & Reitsma, 2007), how children aged 6, 8 and 10 use different target sizes to study their motor performance (Lambert & Bard, 2005) and whether they performed better in cyclic task than discrete task (B. Smits-Engelsman et al., 2002; B. C. Smits-Engelsman et al., 2006). However, Fitt's law is found to be beneficial at the level of motor planning but not at the corrections of ongoing movements (Bertucco et al., 2013). The model counter balances target distance and width but not task constraint in a rapid movement task (Guiard, 2009). Task constraints could be obstacle or challenges rise during hand movement. Therefore, how the motor system deals with other interaction during ongoing hand movement need to be considered in understanding motor behaviour better. As such, Fitt's law may not be ideal to study hand movement performance when dealing with a more constrained environment.

How do the motor system work during interaction? To begin with, the motor system in a human body receives inputs from all sensory and cognitive processes to determine future motor outputs. In other words, it is a motor control process that transforms sensory inputs into consequent of motor commands. This motor control is used in the area of coordination such as planning, organizing and controlling complex motor coordination during interaction (Henderson, 1993). Through frequency of interactions, the motor learning process takes place and gradually, the accuracy execution of a task is improved (Körding & Wolpert, 2004). There are three computational paradigms for motor learning: (1) unsupervised; (2) supervised; and (3) reinforcement learning. In unsupervised learning, while the environment provides input, it neither appoints a target nor any given reward or punishment to measure performance. Unlike in supervised and reinforcement learning, the environment provides both input and output. In supervised learning per se, the output, given by the system, measures the performance error by an explicit comparison of the desired target with the output system. Reinforcement learning on the other hand, uses environment that provides feedback in the form of reward or penalty feedback that accumulates future rewards as a total sum. The distinction between the latter two is that supervised learning measures the performance based on one contact point while reinforcement learning specifies the overall behavior of the performance. It uses a 'trial' and 'error' concept where actions are selected on the basis of past experiences and by new choices (Sutton & Barto, 1998). The motor system learns from the consequences of its trial actions rather than from being explicitly taught to discover which actions yield the most reward (Landy et al., 2012). The trial of actions trained a learner to be a motor expert during interaction in a movement task (Sutton & Barto, 1998).

In a perceptual motor task, Bayesian statistics can be used to estimate the expected value of its actions and update its expectation based on new information in a movement plan. This new information can be sourced from uncertainties in the environment. For children to learn its own motor uncertainty when dealing with constraints during movement, the training requires experience through repetition of task. However, Trommershäuser et al. (2003b) work in a pointing task reported that in the initial phase of the experiment, subjects did not yield any adjustment in the aim point in response to the experience of the movement. Subjects in the experiment immediately changed their movement strategy without having to train when a penalty is imposed near to the reward of the target. Their work shows that subject can perform as well as they did and learned their own motor uncertainty without going through the learning phase when reward and losses were introduced in the motor task. This type of motor task is equivalent to movement planning under risk which share the same formal structure to cognitive decision making (Trommershäuser, 2009). Under this movement planning, subjects are found to be very good at choosing motor strategies that come close to maximize the expected gain (reward and losses) given the costs (motor commands) and benefits (reward) in the motor task (e.g., Trommershäuser et al., 2003b,a; Dean et al., 2007).

A series of studies by Trommershäuser et al. (2003b) explored the connection between cognitive decision making and movement planning under risk and they found out that human participants make optimal motor decisions. In their studies, subjects were required to point out to a target in a reward and penalty landscape which involved precise timing and trade-off between movement time and reward. Subjects motor behaviour were compared to visuo-motor behaviour of an optimal movement planner based on the participants' measured mean and average end point variability. Their studies suggested that the motor system is highly efficient in estimating both the movement variability and the uncertainty in the target position. Subjects take into account their intrinsic motor variability when trying to obtain the best possible movement strategies and therefore, surprisingly select efficient strategies that come close to maximizing expected gain. The selection of movement plan maximizes the utility of sensory, motor and task uncertainty in achieving its optimality (Scheidt et al., 2005). As the sensory is derived from the *mechanism*; motor and task uncertainty is derived from the *ecology*; and reward signal in the motor task is derived from the *utility*; the choice of *strategy* for motor control in my work can be derived from the standpoint of optimal decision making under risk, leading naturally to the application of Statistical Decision Theory.

2.5.2 Statistical Decision Theory

The Statistical Decision Theory is befitting to modeling many realistic tasks concerning cognitive, perceptual and motor tasks in decision making (e.g., Maloney, 2002). In the area of behavioural, decision theoretic has been widely used as computational model in neuroscience, ethology and psychology (Dayan & Daw, 2008). It serves an appropriate common model of how human represent and use uncertainty in a wide range of tasks (Landy et al., 1995; Knill & Richards, 1996; Maloney, 2002). This uncertainty covers the sensory environment and stochastic information that represented in the motor and cognitive tasks. Several groups have proposed that the perceptual properties of the environment can be framed under Bayesian decision theory which is a special case of Statistical Decision Theory (Landy et al., 1995; Knill et al., 1996). This Bayesian approach use probabilities and costs in a statistical system to quantify the tradeoff between various decisions. The probability distribution, for example the pollen count during warm weather forecasting for next day's weather, are prior distributions. Therefore, in a perceptual motor task, Bayesian statistics can be used to estimate the expected value of its actions and update its expectation based on new information in a movement plan. Recent work that use the basis of pointing task following the method of Bayesian decision theory are such as; pointing to a target area with reward and penalty regions (Trommershäuser et al., 2003b), a bet placing to a rotating visual display (Landy et al., 2007), targets in two different shapes placed in different directions (Gepshtein et al., 2007), two penalty regions carrying different penalties (Wu et al., 2006), pointing task under four different time constraints (Dean et al., 2007), time penalty for slower and faster movements (Hudson et al., 2008) and movement task around virtual obstacle (Hudson et al., 2012). These work were all conducted among adult participants. This model of human movement planning is equivalent to decision making under risk.

Trommershäuser (2009) has laid out, in the language of Statistical Decision Theory, of human movement planning in visuo motor tasks. A movement strategy is defined as a mapping from sensory input V to a movement planning $s(V)$ as shown in Figure 2.3. Trommershäuser et al. (2008a) defined the choice of strategy $s(V)$ that maximizes the expected gain (reward or losses) as the following :

$$EG(s) = \iiint g(t,w) p_T(t|s(v)) p_v(v|w) p_w(w) dv\ dt\ dw, \tag{2.1}$$

where W marked the random state of the world (i.e., positions of arm, object and any possible obstacle in the scene). $p_w(w)$ is the prior distribution based on the information observed from the environment and past sensory information. V is the current state of the world with likelihood distribution $p_v(v|w)$ and T is the stochastic movement trajectory obtained from the execution of movement plan $s_T(V)$. The term $g(t,w)$ is the gain resulting from an actual trajectory t in the actual state of the world w. Therefore the term $EG(s)$ takes the maximum expected gain which resulted in the optimality of movement strategy.

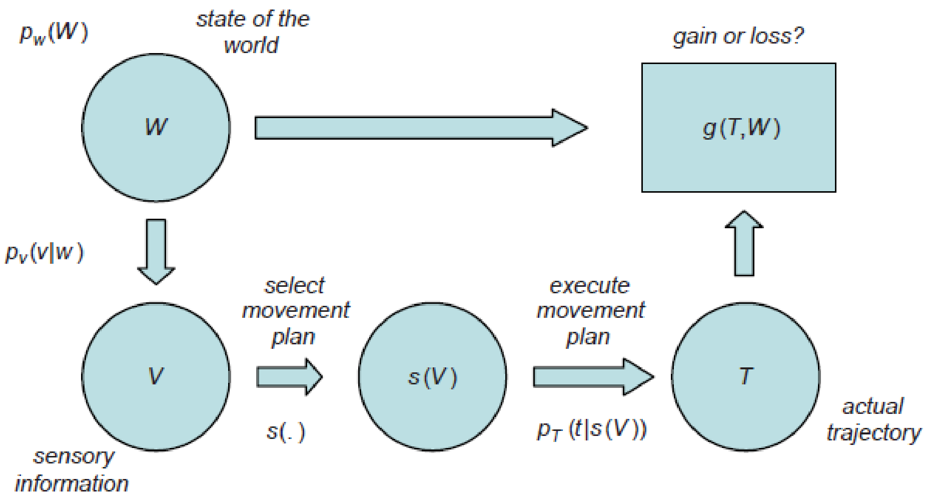


Figure 2.3: Application of statistical decision theory in the context of visuo-motor tasks where a movement strategy is a mapping from sensory input V to a movement plan $s(V)$ to define the best possible movement plan. The term $g(T,W)$ is the gains and losses which are determined by the actual trajectory T executed in the actual state of the world W as taken from Trommershauser(2008).

The work in this thesis is motivated by the movement planning of Trommershäuser et al. (2003b) studies. The model of human movement planning with regards to the drawing movement plan is explained more in Chapter 5 of the second study.

2.6 Summary

At the end of the thesis, I hope to be able to articulate that interaction is adaptive because it is driven by strategies that are constrained by these three components of *utility*, *ecology* and *mechanism*. The lack of ability in any one of the components contributing to the psychological components of the drawing can have far-reaching effects. Therefore all four studies in the empirical work of this thesis incorporated all components into a theoretical framework in order to determine whether children adapt their drawing strategies on a tablet to subjective rewards, their own cognitive and motor limitations and to the limitations of tablet and tablet software. The Adaptive Interaction Framework that derives from the Computational Rational has thus far, as per the literature, been tested in the experimental work involving adult behavioral tasks but not to children. Therefore, the work in this thesis is the first to contribute to children behavioral and interaction task with technology under Adaptive Interaction framework.

The following chapter 3 to 6 explain the work from the empirical ground of the theoretical framework. The purpose of the first study in chapter 3 is an introduction to understand children's drawing behaviour on a tablet given an external reward functions. The aim of the study is to find out whether children are adapt to the reward conditions given. The remaining studies of second, third and fourth empirical work in the following chapters of 4 to 6 try to answer the following main research questions:-

1. How do children adapt their drawing strategies according to their own motor variability and to the limitations of tablet and drawing application?

2. How do a child adapt to the drawing actions according to his/her own motor variability?

3. Does adaptation to motor variability explain age-related changes in drawing performance?

Each study may have further research questions relating to the work that are explained in the respective chapters. In conclusion, the goal of the work in this thesis is to understand and explain children drawing strategies on a tablet under the theoretical of Adaptive Interaction framework. The aim of the work on the other hand, is to investigate whether children adapt optimally under the model of movement planning of Bayesian decision theory.

CHAPTER 3

STUDY 1: DRAWING AND UTILITY

3.1 Introduction

This chapter explains what accounts as utility function in children's drawing task. Utility itself is a quality or state of being useful. A utility function in children's drawing represents a purposeful task that children find it meaningful to accomplish. Drawing by itself can be defined as a goal-directed behaviour. Therefore, a utility function as a drawing activity manifests as a goal that needs to be attained in return for a sense of satisfaction or happiness upon completing it well. Since satisfaction or happiness cannot be directly measured, one way to measure it is through an objective function. This objective function can be regarded as an external reward function that measures the drawing performance. The present study in this chapter suggests that meaningful drawing as a utility function modifies drawing behaviour. Vinter (1999) explained in detail how meaningful drawing affects drawing behaviour in relation to movement sequence in the organization of the drawing action. This is also related to the perceptual, decision and motor processes involved in the act of drawing (Van Sommers, 1984). S. Cox (2009) stated that by focusing drawing as a meaning-making task, it considers the process of drawing as a purposeful action. By realizing the importance of the context of drawing through a utility function, a "product oriented" approach is not only seen as *what* and *why* children draw but also *how* children draw (Einarsdottir et al., 2009). This has been emphasized earlier in the Introduction chapter.

The main purpose of this chapter is to highlight the account of utility function in children's drawing task that can modify their drawing behaviour, in adaptation to context. The utility function in this study takes the external reward as motivational context of drawing action. Specifically, the study finds how children alter their drawing actions in response to the reward conditions introduced when drawing on a tablet with either a pen or a finger. Children like to draw on paper, but how easy is it for them to draw on a touch screen device? More specifically, do children adapt the way they draw on the devices, to their own limitations and to the motivational context of reward? To answer this question, I conducted an empirical study to examine whether children can adapt their drawing actions to their own motor variability and to extrinsic motivations (rewards). This study consisted of drawing tasks that mimic the conventional way of joining the dots on paper but with reward feedback, a significant advantage when drawing on a tablet. Following Mohd Shukri & Howes (2014), the idea was to see how children adapt to the reward conditions when tracing trajectories through the dots on touch screen surfaces using the tip of their finger or a pen. In the next section, I explain in detail about reward as the motivational context of action.

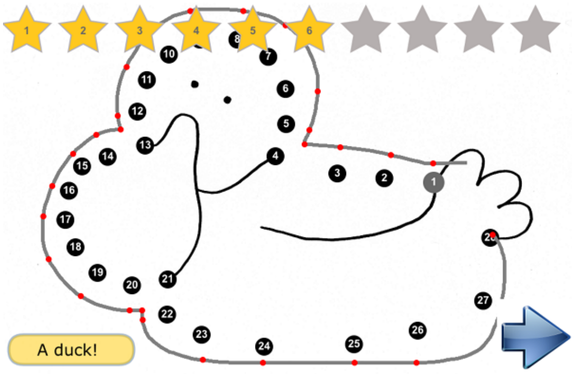
3.2 Reward as a motivational context

According to Shadmehr et al. (2010), imposing a reward can change the state of the body to make movement that feels more valuable. They described in detail how the brain discounts reward as a function of time in movement. When Karniol & Ross (1977) conducted an experiment to test the effects of rewards towards performance of children aged between 4 to 9 years old, they found that there was a relation between the effectiveness of rewards that induce motivation and intrinsic interest to the improvement of performance. This was supported by Weiner & Mander (1978). This shows that by giving reward as feedback in any given task, it can increase engagement (M. Price et al., 2010) and behavioural performance (Felixbrod & O'Leary, 1973). Hence, I chose to include reward function in the drawing tasks.

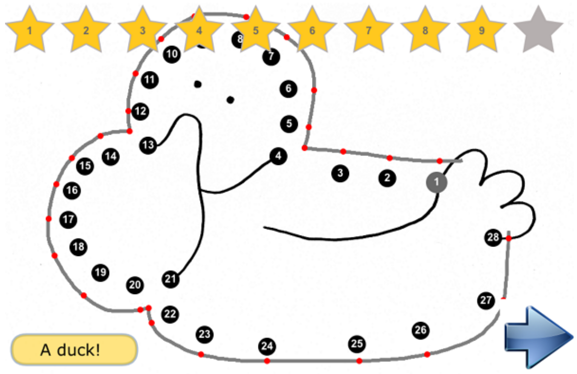
The act of drawing itself without external reward can be rewarding to children. It can become even more rewarding when children received social attention (Einarsdottir et al., 2009). In a traditional drawing on paper, this can be achieved socially or through human interaction. While on a computer system or tablet devices, one way to achieve this is by providing rewards such as number of stars for higher quality of drawings. To study children's drawing behaviour, imposing a reward conditions can help researchers gauge children's competency and performance in drawing besides understanding them better socially or cognitively. According to Kelley et al. (1972), a person will likely be more motivated to complete a task that is extrinsically rewarded. As motivation is partly an important element in children's drawing, it is not unreasonable to suppose that their perception of the quality of what they draw is influenced by their assessment of a drawing fitness. A number of theories asserts that a person's intrinsic interest is discovered when they feel effective on completing a task given a feedback or reward (Festinger, 1954; Smith, 1965; Harter & Zigler, 1974). Other than that, the motivational influences can differ between intrinsic and extrinsic grounds. Although those remain controversial subjects, the purpose of this chapter is to merely highlight the aspect of motivation that relates to behavioral change as an adaptation to context. As external motivation could be perceived as an encouragement to engage in drawing for longer time (Burkitt et al., 2010), drawing tasks used in studies could benefit from these external rewards and feedback.

In imposing an external reward function in children's drawing task, an important question surfaced; "what should be the form of the reward function is suitable to be present for children from different range of age?" The reward function needs to be convenient and simple enough for all users. Also another close attention should be paid to the scoring system. If numbers scoring system is used, would a scoring system with scores from zero to one hundred be suitable? Using larger numbers might be confusing for younger children who may know only limited range of numbers. Alternatively, a representative graphic symbols such as gold star icons can be a better way to represent how well a child did on a drawing task. Nevertheless, it is very essential to know when, what and how much to give reward although apparently this is often an unrecognized problem in design (Janssen & Gray, 2012). The most important goal should be conveying a reward representation that is recognizable to children. Therefore, the approach that I took for this study was a simple scale of number one to ten golden star icons as the reward symbol. While older children may wanted to count the number of stars, I thereof, included numbers together with the gold star symbols in the reward function. Both graphic symbols and numbers inside the stars should suit young and old child users. This design is used in the current reward function of the study. The next section describes the experimental approach in detail.

3.3 The Experiment



a: A *High* Reward Function on the Accuracy-of-the-Contact-Points where if the distance of the contact points are off, the rating star is low.



b: A *Low* Reward Function of Shape-Maintanence where if the distance of the contact points are off but the shape of the drawing lines retain the shape of the drawing figure, the rating star is high.

Figure 3.1: Reward Conditions in Join-the-Dots Drawing Task.

This study investigated the effect of different reward functions on drawing tasks for children. The first reward function measured and rewarded the children depending on how accurate the children hit the dots. The second reward function measured how accurately they generated the shape of the drawing.

Each drawing task was built upon a series of dots that formed a drawing picture where a child-user was required to draw lines connecting these dots according to the order of the numbers. This drawing tasks of *Join-the-Dots*, mimicked the conventional way of joining the dots on paper but with reward manipulations as drawing feedback. There were two types of reward conditions that manipulated the drawing scores. The scoring for reward function in the first drawing tool was achieved by measuring the accuracy of the contact points in drawing lines (see Figure 3.1a) while the reward function scoring in the second drawing tool was by measuring the shape maintenance of drawing figure (see Figure 3.1b). Throughout this chapter, the first reward function is referred to as *High* reward and the second reward function, *Low* reward.

In the *High* reward condition, the accuracy of the contact points were calculated based on the weighted function of least squared errors, where drawing lines need to accurately go through a series of dots to get a perfect score. The contact points distance of the drawing lines were calculated based on the minimal distance of the drawing lines to the numbered dots. If the distance of the drawing lines are far off from the contact points, the number of stars awarded will be low. In the *Low* reward condition, the drawing lines were examined whether they retain the original shape of the drawing figure by measuring with sum-squared error. Under this *Low* reward condition, more stars could be gained for the right shape even if the distance of the drawing lines from the contact points were off by some amount.

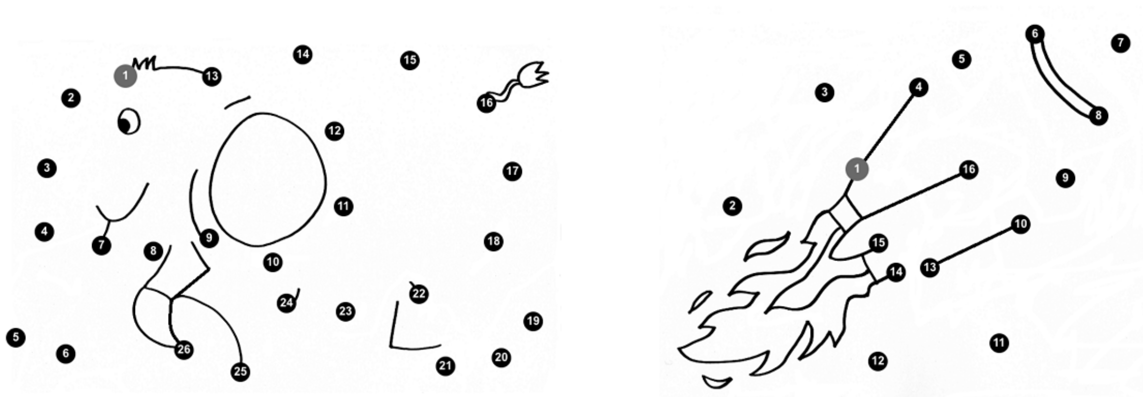
The purpose of the reward manipulation was to examine how children's drawing behaviour differs under two different reward functions with *Low* reward gives easy access to ten stars and *High* reward makes it more difficult to attain ten stars. Hence, *Low* reward in an easy reward and *High* reward the difficult one. The question that interests me is; Are children who draw under the *High* reward function be more motivated to draw better than children drawing under *Low* reward function? Therefore, the hypothesis of the study is derived; *children are motivated to draw more accurately given High reward than Low reward*. This study's results proposes that when the reward of high number of stars are harder to achieve, children would be more motivated to draw better by drawing more accurately to get high number of stars. However, when the reward of higher number of stars are easy to achieve although children draw less accurately, they can become less motivated to draw. The study also investigated whether there will be performance differences between drawing with a finger and using a pen. Given that drawing using a pen requires a child to get grip of the pen while a child who draws with a finger requires one single finger when drawing on a tablet, the differences in the accuracy or output of the line strokes are expected. It could be assumed that the accuracy of the drawing lines are better when a child draw using a pen than with their finger as they get a better grip and control when drawing. Therefore, do children who use a pen draw more accurately than those using their fingers? The hypothesis is derived; *children who use a pen to draw, are more accurately in their drawing than those who draw with their finger*. I also took a closer look and examined a few other parameters in children drawing such as their drawing scores, stroke speed, completion time, penlifts and mistakes made compared to the children's age when drawing on a tablet.

3.4 Method

3.4.1 Apparatus

The experimental setup used was an iPad Air tablet device with 10.1-inch wide screen that was connected to an Apple MacBook-Pro 13-inch laptop through a USB cable. The 10.1 inch screen size was selected as it was big enough for most children to comfortably draw and not too large for them to handle or possibly causing them difficulty to focus on the drawing task. The drawing application was loaded by a Safari web browser on the tablet device via a stable internet connection. Subjects either used their fingertips or a stylus pen to perform the drawing tasks and were given complete freedom and flexibility to sit comfortably while drawing. All input and data of subject's performance on the drawing tasks were transferred to the laptop through the USB cable using Safari web inspector development tool.

3.4.2 Stimulus

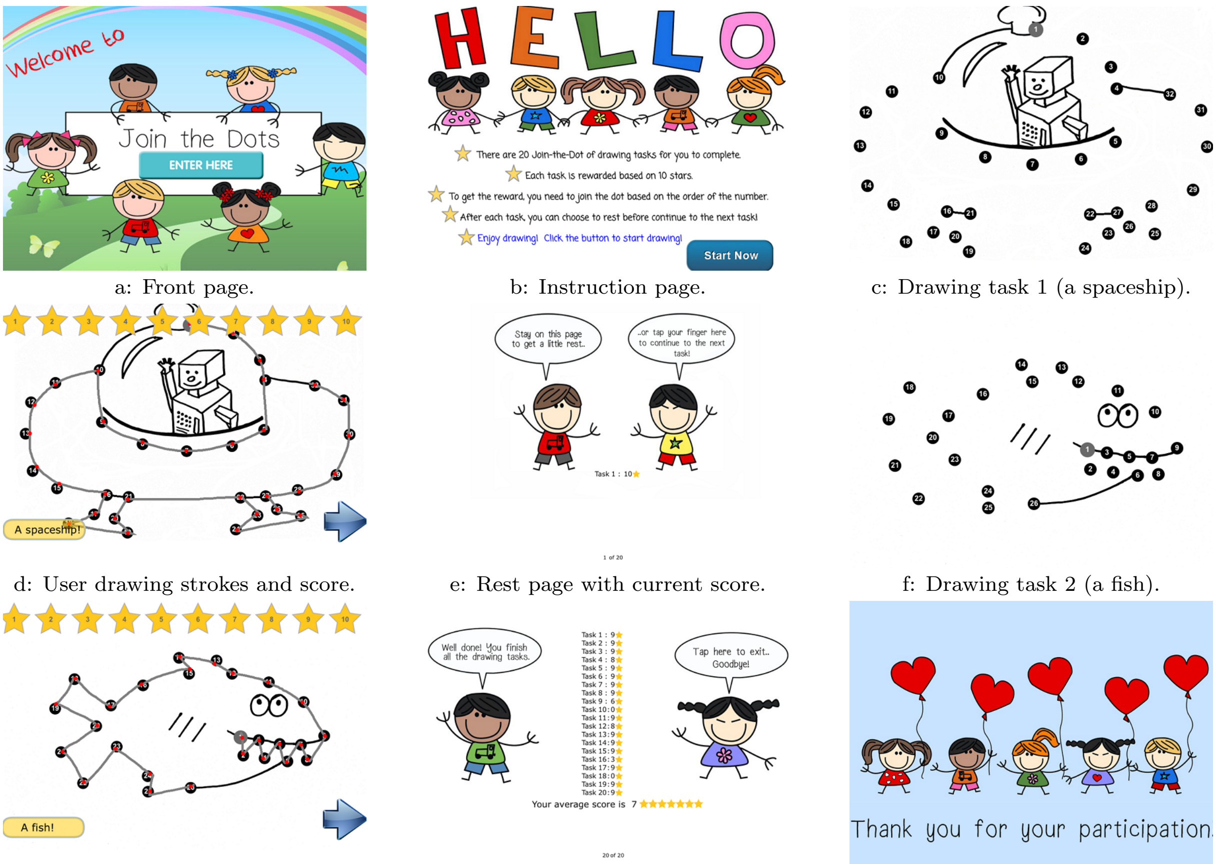


a: An elephant. b: A rocket.

Figure 3.2: Join-the-dots drawing picture

The *Join-the-dots* drawing application was developed using HTML5 and JavaScript. Two drawing applications were built; both having similar tasks but two different reward functions, *High* and *Low* rewards. There were 20 drawings comprised of 10 vehicles and 10 animal shapes displayed in random order (Example from each category are shown in Figure 3.2). There were a good mix of drawings that have large number of dots with shorter distance and fewer number of dots but with larger distance between them. This caused the number of dots in each drawing to range from minimum of 15 dots to a maximum of 35 dots. Each dot were numbered to guide the subjects to draw a line from one dot to the next one based on their order. These dots have a black circle backgrounds with a bold white numbers. The size of the first dot is slightly bigger than the rest of the dots and unlike other dots, it had a grey background to be conveniently located by the subjects. Upon completing all the tasks successfully, an overall reward of ten stars would be displayed on top of the page with a text naming the picture shown on the bottom-left corner. The ten stars for the overall reward were grey in color, with the overall score or number of stars gained was shown by highlighting or changing the color of stars from grey to golden yellow.

3.4.3 Procedure



a: Front page. b: Instruction page. c: Drawing task 1 (a spaceship).

d: User drawing strokes and score. e: Rest page with current score. f: Drawing task 2 (a fish).

g: User drawing strokes and score. h: Score board. i: End page.

Figure 3.3: Drawing application *Join-the-dots*

The drawing application started with a main page followed by a simple instruction page. A *Start Now* button was placed on the instruction page which when tapped, the first drawing task would be loaded. The subject would then need to start performing the drawing task by drawing the lines from one dot to the next based on their order. The drawing time was recorded starting when the finger or pen was tapped on the first dot until the final dot was touched. The application also recorded the number of pen-lift, the number of times that the finger or pen used by the subject was lifted from the screen. Once a drawing was completed, the screen would halt and the number of stars would be displayed together with a word describing the object drawn. An arrow shaped button in the bottom-right corner of the screen would be visible for the subject to proceed to the next page. The next page was a *rest page* which appeared after every drawing task for subject to take a break after each drawing task. Altogether there were 20 drawing tasks to complete in the experiment. At the end of the session, a page with detail scoring for every drawing task would be shown together with the overall score. The last page thanks subjects for their participation. Figure 3.3 above shows the order of the tasks on the drawing procedures with two drawings as example.

3.4.4 Experimental Design

High Reward	Finger	1	5	9	2x1
Low Reward	Finger	2	6	10	2x1
High Reward	Pen	3	7	11	2x1
Low Reward	Pen	4	8	12	2x1

Figure 3.4: Between design experiment.

The experiment was between participants design with two independent variables: reward manipulation(*High* and *Low*) and medium input(*Finger* or *Pen*). There were 4 experimental groups; *High Reward* with *Finger*(*A1B1*), *Low Reward* with *Finger*(*A1B2*), *High Reward* with *Pen*(*A2B1*) and *Low Reward* with *Pen*(*A2B2*). It was a one data point per participant, a two-by-two analysis of whether subject's drawing action was affected by using *Finger* or *Pen* and whether it was affected with a *Low* or *High* rewarding score. Figure 3.4 above shows the design layout of the experiment. On average, the experiment lasted about 40 minutes to 1 hour per participant.

3.4.5 Pilot Study

The first pilot study was conducted on 3 adults; all were postgraduate researchers from School of Computer Science at University of Birmingham. The purpose of the first pilot study was to identify any problem that could occur while performing the drawing task on the drawing tool. During pilot testing, there was a minor error on the drawing strokes behaviour when one of the subject tried to draw not according to the right numbering order of the dots. Other than that, subjects gave valuable feedbacks on the overall design of the drawing tool. Some improvement were made on the interface and interaction of drawing tool and the algorithm of the reward functions.

The second pilot study was conducted on 4 children participants comprised of 2 boys and 2 girls, intended to have a closer feel and situation of the real experiment. They were arranged in the order of group *A1B1*, *A1B2*, *A2B1* and *A2B2* according to table in Figure 3.4. The first pilot child-user was a girl aged 6 years old, the second was a boy aged 9 years old, the third was a boy aged 8 years old and the fourth was a girl aged 5 years old. The pilot test was handled in a manner of how the real experiment would be conducted. The purpose of the pilot test was to ensure the following criterias:-

i The experimental tasks and instructions were clear to children.

ii The overall interaction of child-user and drawing application was smooth.

iii Usability of the drawing tool on wide range of children age.

iv The overall session with a child-user would be was successful with minimal error and interruption.

The first three pilot child-users did very well in completing the drawing tasks. However the scoring system were rather strict giving less number of stars as they deserved was found to be a little bit too stringent, hence giving them rather low number of overall stars than what they actually deserved. The fourth pilot child-user could not attempt the drawing task as she was not familiar with numbering order. Therefore, these improvements and changes were made on the following criteria after the pilot study:-

i The rating score were tested a few times to give the right number of stars to the drawing output.

ii The instructions on the drawing tool were made easy and concise to understand.

iii Join the dots activity on paper were introduced before the experiment to ensure child-user understand the numbering order.

3.4.6 Subjects

Thirty four children participated (15 boys and 19 girls) with age ranging from 5 to 11 years old. One participant was discarded from the analysis due to not following the order of the task, thereof, thirty three children participants were involved with a mean age of 7.76 years (SD=2.0 years).The children were from a mix of Asian backgrounds and they all attend primary schools in Birmingham, UK. These children participants on an average used two hours of touch screen devices daily. Figure 3.5 shows the age distribution of the participants.

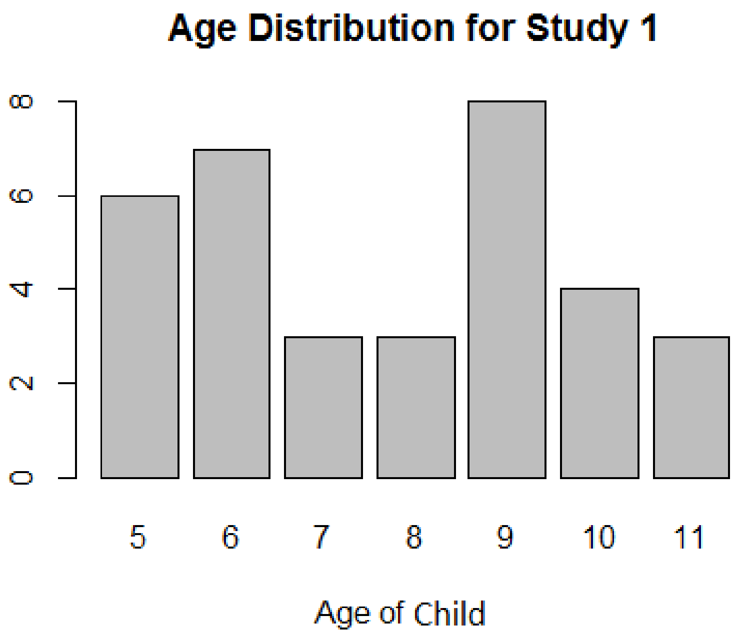


Figure 3.5: Age distribution for children participants in study 1.

3.4.7 Instruction

All parents had given their informed consent to allow their children to participate in the study. Participants also gave their informed consent verbally and in writing prior to the session conducted during the experiment. They were briefly informed on how the task should be completed and were then asked whether they had any experience using touchscreen devices. Those without or having less experience were given a tablet to familiarize themselves using the touchscreen device for about ten minutes. Later, they had a warm-up session of join-the-dots task on paper using a pen or pencil. This was to ensure that subjects were familiar with numbering order from 1 to 50 and understand the basic concept of a joining-the-dots task. Once they completed the tasks on paper, they were assigned to one of four groups. The group assignment was based on the order of participants. The first subject was assigned to *A1B1*; second subject assigned to *A1B2*; third subject assigned to *A2B1*; fourth subject assigned to *A2B2*; fifth subject was again assigned to *A1B1* and the pattern continued for the rest of the subjects. All were unaware of the hypotheses under test. When subjects completed the tasks, they were each given a form to fill in and provided information on their background and the amount of time spent drawing on paper and tablet daily. At the end of the session, they were each given a token of appreciation for their participation.

3.4.8 Data Analysis

In the analysis, I examined the effect of the scoring system between *High* reward and *Low* reward and whether there is an effect on scoring when drawing using a *finger* or a *pen*. Other parameters that were observed and recorded were drawing time, number of pen lifts, drawing speed and drawing mistakes according to their age difference. The drawing time for each task was recorded once the subjects hit the first dot until they lifted their pen or finger from the touch screen after they reached the last dot. A pen-lift is defined as an action when the subject lifted their pen or finger from the touch screen after they had started a drawing task and yet to finish the task. The drawing speed was calculated based on the distance traveled by the finger or pen from one dot to the next divided by the time taken to connect those two dots. The normality of all continuous data were assessed prior to analysis.

3.5 Results

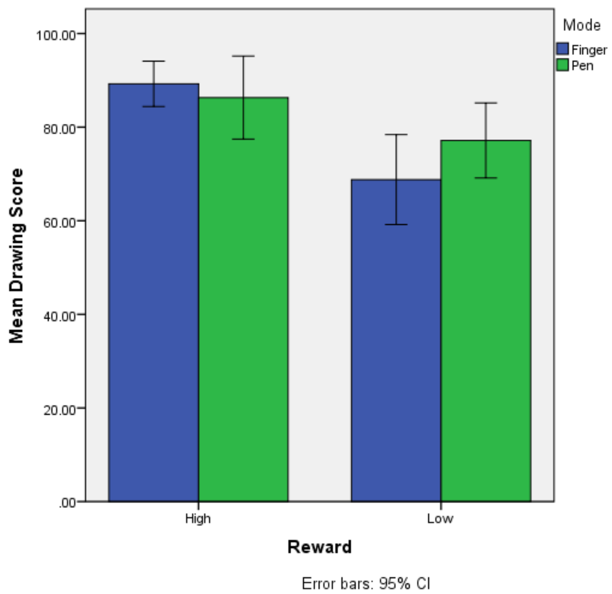
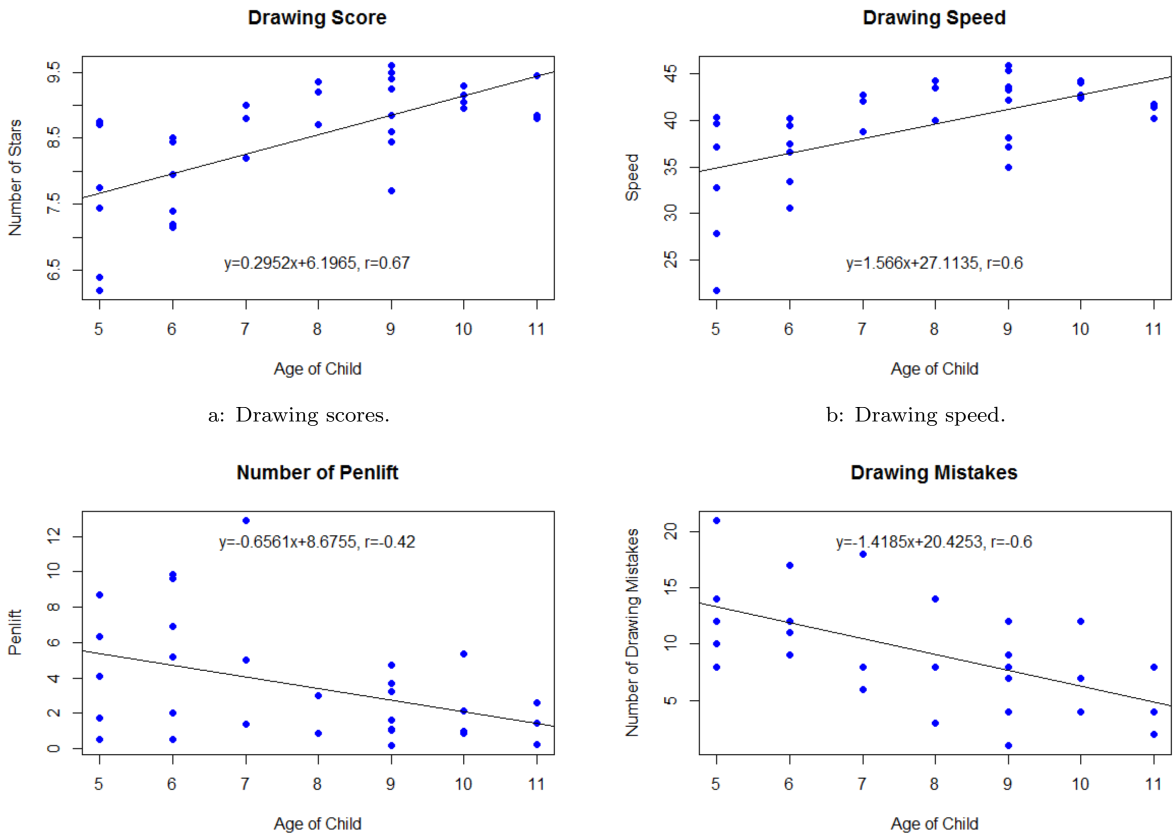


Figure 3.6: Participant's average drawing score according to the reward function(High/Low) and mode of drawing(Finger/Pen).

A two-way between-group analysis of variance was conducted to examine the effect of reward functions and drawing medium towards the score of the drawing tasks. There were 33 participants (n=33) data. There was a statistically significant main effect for the reward functions; $F(1{,}29)=18.485$, $p<0.0001$ with *High* reward having a mean score of 89.25 for finger, 86.31 for pen and *Low* reward having a mean score of 68.79 for finger, 77.15 for pen (see Figure 3.6).There was no main effect for drawing mediums; $F(1{,}29)=0.619$, $p=0.438$ and no interaction effect between the reward functions and drawing mediums, $F(1{,}29)=2.687$, $p=0.112$. The result shows that child users whether they were drawing using a finger or a pen, scored higher in *High* reward than in *Low* reward but there was no effect on the scoring due to the selection between the two medium inputs.

The relationships on children's drawing behaviours such as drawing scores, drawing time, pen-lifts, speed and mistakes among children were also investigated using Pearson product-moment correlation coefficient. Preliminary analyses were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity. There was a strong positive significant correlation between the age of children and number of stars, $r=0.67$, $p<0.0001$ where older child users scored higher than younger child users (see Figure 3.7a). There was a moderate significant negative correlation between age of children and number of penlifts, $r=-0.419$, $p=0.019$ (see Figure 3.7c) and a strong positive significant correlation between age of children and drawing speed, $r=0.597$, $p<0.0001$ (see Figure 3.7b). Younger child users made more number of penlifts and drew slower than older child users when performing the drawing tasks. Younger child users would probably take more time to draw accurately than older child users due to their generally slower speed. Drawing time however did not show any correlation with age of children although older child users drew faster than younger child users. However, during the experiment, some of the child users were observed to pause drawing at the contact points without lifting their finger or pen before making the next drawing move. When child users pause between contact points, the drawing time was still recorded. Therefore, this contributed to making the overall drawing time for younger and older children about the same.

There were a few drawing mistakes that were identified in the study. However, the most significant mistakes that child users committed were trailing their non-drawing fingers while drawing and drawing the lines not according to the numbering order. There was a strong negative significant correlation between age of children and number of drawing mistakes, $r=-0.603$, $p<0.0001$ which indicated that younger child users make more mistakes when drawing on a tablet than older child users. For drawing mistakes with respect to out of order, child users during the experiment were observed to be likely making assumptions of what would the whole picture looked like from the outline of the contact points where they would verbally inform the instructor before attempting to draw. This would affect how they plan their drawing lines by not following the ordering numbers.



a: Drawing scores.

b: Drawing speed.

c: Number of penlifts.

d: Drawing mistakes.

Figure 3.7: Drawing actions based on age distributions.

3.6 Discussion

The aim of the work reported here is to understand the effects on children's drawing strategies to the reward functions introduced and how they would perform when drawing on a tablet using two different medium inputs, a finger and a pen. The result suggested that child users were more motivated to draw better when the number of stars or reward were harder to obtain rather than when it is easier to do so. The selection on the medium of drawing input whether with a finger or a pen did not make any significant difference to the drawing star scores. According to Tu et al. (2015), drawing with a pen mostly outperformed finger in smaller surface of detailed area. The fact that the drawing tasks in this study measured the lines of contact points that are basically the outline of a whole drawing figure, no differences occurred between the two medium inputs.

How could we be sure that children who did the *High* reward were more motivated to draw better than those who did the *Low* reward? Perhaps children in both conditions had understood that they need to hit the dots as accurate as they could and that the same scoring system should quantified the differences between the group. Additional analysis had been made where both groups were tested for each separate scoring function of *High* reward (accuracy of hitting the dot), *Low* reward (shape of the drawing) and a combination of both type of rewards where *High* and *Low* rewards are embedded together to test the performance of the drawing lines. All tests have shown that there were no significant differences in the result with both *High*'s, $F(1{,}29)=4.057$, $p=0.053$; both *Low*'s, $F(1{,}29)=0.32$, $p=0.576$ and both combination of *High-Low* are $F(1{,}29)=1.999$, $p=0.168$. However, the result for *High* reward function to both groups is showing close to significant where the *High* group scored higher in both medium of drawing than the *Low* group. This shows that children participants in *High* group were motivated to draw more accurately in hitting the dots than those in the *Low* group. Since children participants in the *Low* group were not punished according to how accurately they hit the dots, they were less likely to draw the lines closer to the dots. This fit the purpose of the main objective of the experiment, where children were adapted to the reward functions introduced. The result for *Low* reward function tested toward both groups shows that children in overall tried to maintain the shape of the drawing lines. The black dots as reference of the drawing figure are closed to each other making it hard for children to deviate their drawing lines from the point of reference. When both *High-Low* functions were combined to test their performance, both average score were about the same yielding no significant differences showing a balance score between the first two additional tests. The main result earlier showing highly significant differences among the two groups with different reward functions introduced can be firmly concluded that children do adapt to the reward functions introduced. Specifically, children in *High* group were more motivated to draw more accurately than those in the *Low* group.

Children's drawing behaviours and attributes were also investigated apart from the main finding. Younger child users tend to make more penlifts when drawing and attempted more drawing mistakes than older child users. They made unintentional touches with trailing fingers and thumbs (McKnight & Fitton, 2010; Anthony et al., 2012) and drew line segments in out of order. Older child users generally scored better than younger child users. Although they draw faster than younger child users, they were observed to stop at the contact points without lifting their finger or pen when drawing before making the next drawing move. The precaution of stopping on the dots reflects more on the cognitive aspect of drawing rather than fine motor skill (Lange-Küttner & Reith, 1995). This would yield about the same drawing completion time overall with younger child users that made pen lift. The overall result regarding children's drawing behaviour is supported by Vatavu et al. (2015) that reported children's touch screen performance in task completion time and accuracy improved with age; and that due to increased motor maturation and improved drawing proficiency, older children tend to draw faster than younger children (J. Laszlo & Bairstow, 1983; Lin et al., 2015). The result strengthened and supported the existing attributes regarding children's drawing behaviour from an empirical approach and an external reward function.

Drawing itself is a rewarding task to children whether or not if there is an external reward system. Children participants were seen to engage in the drawing task even if they were to receive a lower rating score. However, with the reward conditions, not only it helped to motivate child users to draw better and for longer but it can conveniently quantify their performances. Perhaps with the external reward functions, younger child users were able to complete all 20 drawing tasks altogether which could be harder without the external reward imposed. The reward function and context of drawing are deemed to be successfully designed as they attracted many child users that wanted to continue using the drawing application even after completion of their sessions.

3.7 Conclusion

The purpose of this study is to investigate children's drawing actions on a tablet given external reward conditions when drawing using a pen or a finger. The experiment provided encouraging evidence that children do adjust their drawing actions to the reward functions. Its' results seem to be pointing to that children adapted to the reward functions introduced. Therefore, the next questions to be answered are, can they adapt optimally? What if besides gaining rewards of higher number of stars, there is also a penalty effect nearby? Also, what can we observe if time limit is introduced in the tasks and make the drawing tasks more challenging? How would children plan their drawing actions to gain higher rewards within these limitations? These possibilities give rise to a rapid drawing movement task. As these are the motivations for my next study, I can use the paradigm introduced by Trommershäuser, Maloney, & Landy (2003b) in my next experimental work.

CHAPTER 4

STUDY 2: DRAWING AND MOVEMENT PLANNING

4.1 Introduction

This chapter describes a drawing task that is similar to the previous study of join the dots but with both reward and penalty effects. The study in Chapter 3 shows that children do adapt to reward conditions introduced in the drawing tasks. In this second study, we are hoping to answer the next question, do they adapt optimally? What will happen if they also have to avoid penalty areas in the drawing tasks that will lower their score? Previous study shows that children are definitely adaptive to the reward conditions. Therefore, the experimental work in this second study investigates not only whether children can adapt to the reward and penalty effects but also whether they can adapt optimally. Specifically, how do children adapt their drawing strategies on a tablet, to their own motor and cognitive limitations and to the motivational context of reward and penalty effects?

In this second study, the approach used dealt specifically with how children draw; following closely the method and natural variant of Trommershäuser et al. (2003b) studies. The method is used to examine children's drawing movement given reward and penalty effects in a rapid movement task. The objective of this study is to explain how children plan their drawing strategies to the penalty and reward signal, when under time pressure and whether they are adaptive to reward and feedback. The main purpose of this chapter is to describe the model of movement planning used in children drawing movements as detailed out in the *strategy space* of theoretical framework in chapter 2. The next section explains the model of Movement Planning in detail.

4.2 A Model of Movement Planning

A model of motor planning concerns on the movement planning that addresses the problem of defining and finding the optimal sequence of motor commands given a pre-specified goal. In planning a goal-directed movement, the motor system is required to make a rapid and good motor decision to pick one of many possible motor programs. This motor program is a strategy that includes a choice of goal bound trajectory with an ongoing visual feedback during the movement. During this planned movement, the motor program takes into account the consequences of possible motor errors (Wu et al., 2006) that resulted from the sensory of uncertainty (Trommershäuser et al., 2005). When executed under a tight time constraint, the motor responses are varied (Fitts & Peterson, 1964; Meyer et al., 1988). This outcome of movement planning is called a visuo-motor strategy.

In Bayesian decision theory, the visuo-motor strategy relies upon the goal of movement, the planned duration, the possibility of visual feedback during movement, previous training and intrinsic uncertainty in the motor system (Trommershäuser et al., 2003a). The outcome of any planned movement is also subject to sensory and motor variability (Hudson et al., 2008). Consider a pointing task where the hand needs to move quickly to a target. The task becomes more difficult if the movement time is set to be shorter, the target is smaller or the distance to the target is farther. Subjects take uncertainty into account by selecting a movement time that would allow the target to be hit. For example, the movement time is prolonged when the size of the target is smaller as predicted by Fitts law (Fitts, 1954). According to Meyer et al. (1988), in a natural reaching condition, subjects select a movement time that would allow them to reach the target well by considering the uncertainty associated in the movement. Evidence from their work has shown that motor system takes into account its own uncertainty in movement planning. Due to this uncertainty, the motor noise during the hand movement causes a planned movement to differ from the original planned movement. Hence, each movement outcome becomes a probability to the choice of movement plans, thus making the exact outcome of hand movement a stochastic choice.

In Trommershäuser et al. (2003a) studies, subjects were required to hit a small target area on a computer screen where if successfully hit within a certain time limit they would yield a small monetary reward. A penalty region was placed nearby the target area as an obstacle to the task, whereby if a subject accidentally hit the penalty area would result in a loss. If movement exceeds time limit, a high penalty is incurred. Since movement needs to be rapid, subject may probably hit the penalty area. When a high penalty point is placed next to a small target area, adults are known to alter the motor plan. In particular they shift their aim point so as to avoid the penalty region. Therefore, given a similar condition in a children's drawing task, do they alter their aim point according to reward and penalty effect? Will they be willing to risk collision with an obstacle and receive penalty points if the reward associated with it increased upon completing it? I attempt to answer these questions according to the model of a movement plan.

If we take a situation where a subject is limited to a set of possible choices in reaching an object, how does the subject plan to attain the intended goal? There are several possible movement plans or strategies that the brain has to select in planning this movement. Statistical and Bayesian decision theory can be utilized to find the best possible choice of movement plan. Firstly, the subject need to have prior information of the object location and obtain accurate sensory information of the environment such as whether there is any obstacle to avoid. Secondly, the motor plan needs to specify intended properties of movement for the arm and body to reach the object such as direction, velocity and other movement properties estimated from the sensory acquired. While the accuracy is determined by velocity of movement (Fitts & Peterson, 1964), subject can accurately control his own movement depending on how fast or slow the movement is. Thus, faster movements would require larger control signal and are more varied in the motor outcome, resulting in a well-known speed-accuracy tradeoff (Harris & Wolpert, 1998). At the end, the success or failure of the movement takes into account the sensory information obtained, possible gains and losses associated with possible motor outcomes and the error in executing a motor response (Tassinari et al., 2006; Dean et al., 2007).

The goal of a movement planning is to select a movement trajectory that optimizes the visuo-motor movement strategy. Equation 4.1 by Trommershäuser et al. (2008b) is the optimal visuo-motor strategy S that is used to maximize subject's expected gain G. The Gain is the total of reward and penalty points. This movement strategy is a visual motor strategy that forms a sequence of motor commands involving intermediate goal in space and time.

$$\Gamma(S) = \sum_{i=1}^{4} G_i P(R_i|S) + G_{timeout} P(timeout|S) \tag{4.1}$$

The probability of $P(R_i|S)$ is used to define the choice of strategy S with reaching region R_i before the time limit ends (t=timeout). If the task is completed beyond the time limit, a penalty $G_{timeout}$ is given. $P(timeout|S)$ occurs as a probability of a visuo-motor strategy S that leads to a timeout.

4.2.1 A Plan for Drawing Movement

The drawing movement plan consisted of a visual motor strategy, S, where S is selected based on the mean end point of drawing movements within time. For any time t, the drawing movement trajectory, $\tau(T)$ is a result of a fingertip contact point or position in time and 2-dimensional drawing space with τ:$t \rightarrow [x(t),\ y(t)]$. When motor strategy is executed, it imposes a probability density, $P(\tau|s)$ that is a possible drawing movement trajectories on a 2-dimensional drawing space. Refering to Trommershäuser et al. work, this probability density $P(\tau|s)$ of drawing movement is likely to be affected by the interactivity of the drawing task itself from the goal of drawing and visual drawing feedback; experiences from performing the drawing trials and intrinsic uncertainties embedded in the motor system. The drawing task environment contains regions that carry penalty or reward points that were explicitly known to the subject. Trommershäuser et al. used the term gain, G_i, i = 0,...,N to refer to both rewards and penalties point incurred from different regions, R_i, i = 0,...,N. The optimal of visual-motor strategy S occurred when subject maximizes the expected gain $\Gamma(S)$ on any drawing trials.

In the drawing task, each subject is required to draw a line from a starting point towards a target region within a time limit. On every trial, there is a penalty region placed near to the proximity of the target region. The penalty region is located either overlapping the target region or next to it. Each drawing action that is completed within the time limit has four possible outcomes of reward and penalty value represented as gains, G:

- **The non-overlapping target is hit**. If region R_0 is hit, subject receives a high reward of G_0 stars (R_0 >0).
- **The non-overlapping penalty region is hit**. If region R_1 is hit, subject receives a penalty of low reward as G_1 stars (G_1 >0).
- **The overlapping target and penalty region is hit**. If region R_2 is hit, subject receives a medium reward of G_2 stars (G_2 >0).
- **The outside region is hit**. If region R_3 is hit, subject does not received any reward ($G_3 = 0$).

Late responses or failure to complete the drawing action within the time limit incur the same penalty as G_3; where no reward is given. The possible visual-motor strategies S is denoted by the resulting mean end point (x,y) of the contact point on the touch screen; yielded as the *aim point* of the subject. In order to predict the optimal *aim point* of a drawing movement, the drawing end point should maximize the expected gain function as shown in equation 4.2 followed by 4.3.

$$\begin{aligned} L(x,y) = {} & G_0 P(R_0 \mid x,y) + G_1 P(R_1 \mid x,y) \\ & + G_2 P(R_2 \mid x,y) + G_3 P(R_3 \mid x,y) \end{aligned} \tag{4.2}$$

We can ignore the constant G_3, the outside region which gives a 0 point.

$$\begin{aligned} L(x,y) = {} & G_0 P(R_0 \mid x,y) + G_1 P(R_1 \mid x,y) \\ & + G_2 P(R_2 \mid x,y) \end{aligned} \tag{4.3}$$

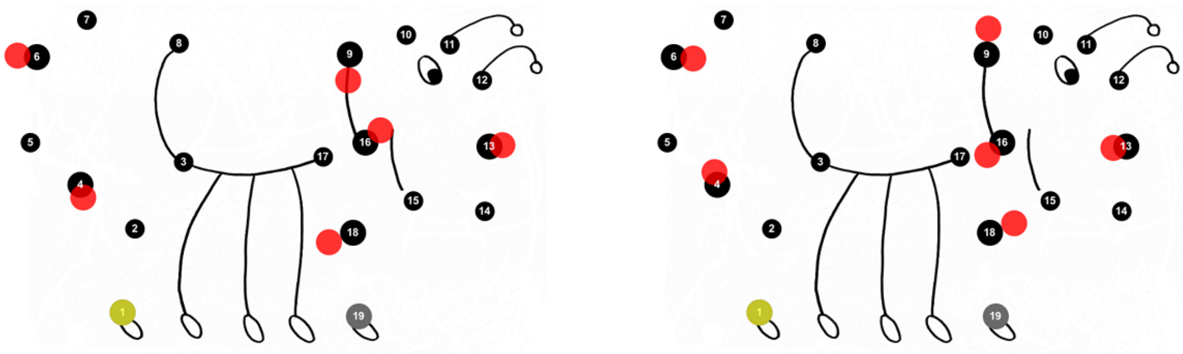
The movement goal as in equation 4.3 is used when reward and penalty region is reached within the time limit. The penalty and reward points are determined based on the position of the end point that passes through the border of the target areas. Strategy S is identified as the aim point resulted from the plane ($\overline{x}$,$\overline{y}$) which resulted to a particular choice of strategy S of mean end points. When there is no penalty imposed, the maximum expected gain of *aim point* (the mean end point) is at the center of the target region. When the penalty is imposed or set as non-zero, the maximum expected gain of aim point shifts away from the penalty region, hence away from the center of target region. The optimal shift occurs when the magnitudes of motor variability is larger, the penalty region at its closest distance to the target and with greater penalties imposed (Todorov, 2004; Trommershäuser et al., 2005; Tassinari et al., 2006). For children's drawing task, the focus was only on the penalty conditions of their distances to the target region. Therefore, the hypothesis of this study is derived; *Subject make a larger shift when the penalty region is closer, a moderate shift when the penalty region is less close and a large shift when the penalty region is further away; from the centre of the reward region.*

4.3 Method

4.3.1 Apparatus

Refer to Section 3.4.1.

4.3.2 Stimulus



a: The first ant.

b: The second ant.

Figure 4.1: Join-the-dots drawing pictures with penalty regions on different sides of the target region.

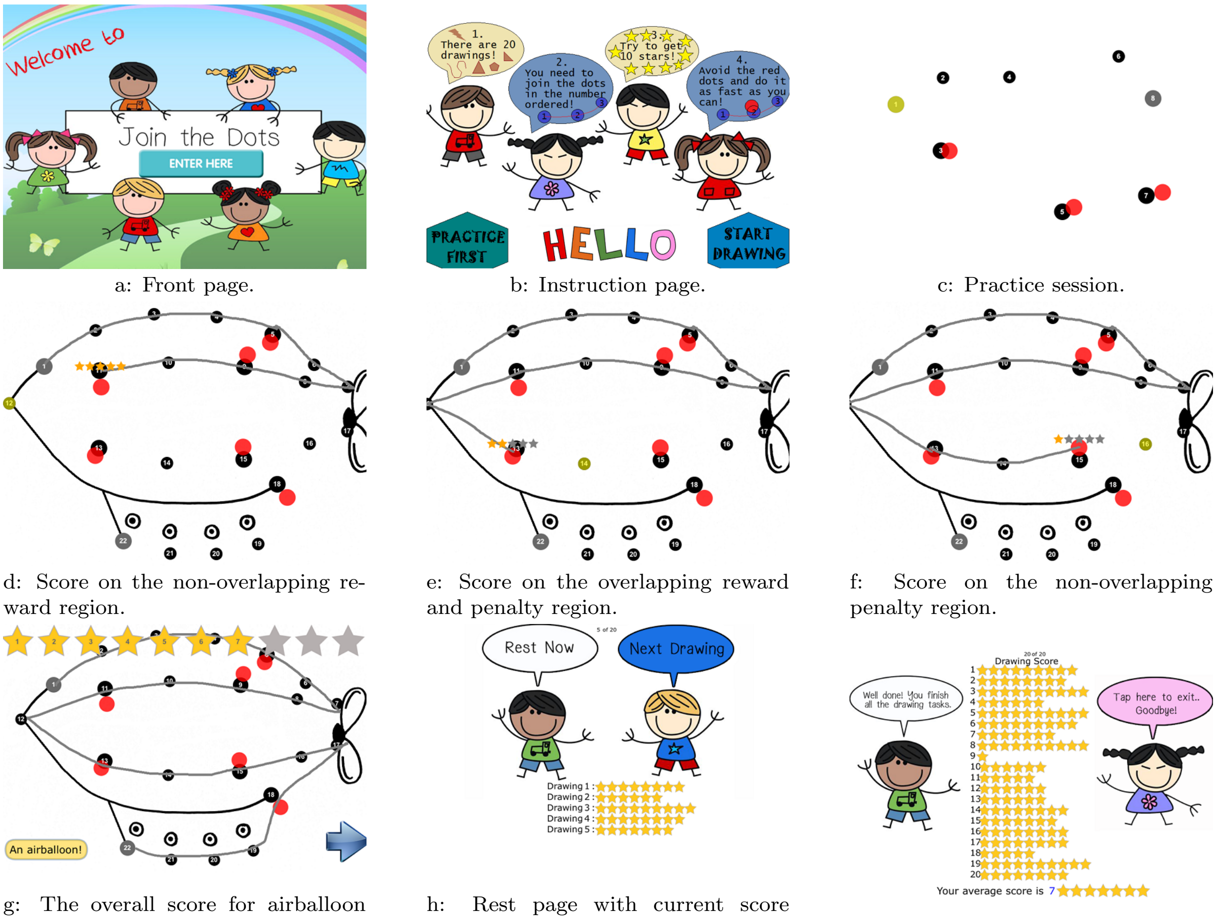
A drawing application of *Join-the-dots* were developed using HTML5 and JavaScript similar to the first study. Ten drawing pictures of join the dots from the first study were chosen where each drawing was repeated twice to make a total of 20 drawing tasks altogether. These ten drawing pictures were chosen based on the least error mistakes occurred from Study 1. The drawing pictures were displayed in random order. For this drawing application, the red dots were imposed near to several black dots. The red dots worked as penalty region while the black dots acted as target region. The red dots were placed in three different proximities which are *close*, *medium* and *far*. The *close* red dot was placed 0 unit CSS pixel of radius from the first black dot, the *medium* red dot was placed 0.5 unit CSS pixel of radius from the second black dot and the *far* red dot was placed 1 unit CSS pixel of radius from the third black dot (see Figure 4.2). The red dots were placed starting with *close*, *medium* and *far* distance away from the first three black dots and the same pattern was repeated again to the next three black dots in every drawing task making it altogether 6 pairs of a joined red and black dots. Each pair of red and black dots was followed by one or more singular black dot before the other next pair. The singular black dot was one unit size smaller. These red dots were randomly placed either to the left or the right side of the black dots. Since each drawing picture was repeated twice, so were the placement side (left or right) of the 6 pair of dots. If in the first drawing the red dots were placed on either to the left or right side of the black dots (see example in Figure 4.1a); for the second of the same drawing, the red dots would be placed to the opposite of these sides (see example in Figure 4.1b).

a: The red penalty region on the left side of black target region with distant of near, medium and far.

b: The red penalty region on the right side of black target region with distant of near, medium and far.

Figure 4.2: The penalty and target region used in *Join-the-dots* drawing tasks adapted from Trommershauser et al., 2003. The black area (non-overlapping reward region) gives 5 stars, the red area (non-overlapping penalty region) gives 1 star, the maroon area (overlapping reward and penalty region) gives 2 stars and background area (outside) gives 0 star.

4.3.3 Procedure



a: Front page.

b: Instruction page.

c: Practice session.

d: Score on the non-overlapping reward region.

e: Score on the overlapping reward and penalty region.

f: Score on the non-overlapping penalty region.

g: The overall score for airballoon drawing task.

h: Rest page with current score board.

i: Final score board.

Figure 4.3: Drawing application *Join-the-dots* with timing and penalty region constraints.

The drawing application started with a main page followed by a simple instruction page. A *Start Drawing* button is placed at the bottom-right hand corner of the instruction page which when tapped, the first drawing task would be loaded. There was also a *Practice First* button at the bottom-left hand corner of the same page. Subjects were required to go through the practice session first. Once the practice session was completed and the subjects were ready, they would start the actual session. In each drawing task, the first dot was highlighted yellow for subject to easily spot where to initially placed their finger or pen to start drawing. There would be no traces of strokes if the pen or finger was placed elsewhere other than in the area at the first dot. When the first dot was touched, the yellow highlight on the current dot would disappear and the next target dot would be highlighted. The purpose of highlighting the dots was to conveniently guide subject to find the next targeted dot. If the next target is a pair of red and black dots, a fading of five tiny yellow stars would start to appear when subject touched the current dot. The fading stars effect was an indication that the time had started for subject to draw and reach the targeted dots on time. If the subject's end line reached the non-overlapping target black dot within time, the subject would get five stars. If the end line reached the overlapping black and red dots within time, the subject would get two stars but if it reached the non-overlapping red dot, only one star would be gained. If the drawing line reached outside the pair dots region or fail to reach the target within time, there would be no star gained. Subject would draw through 6 pairs of red and black dots to complete each drawing task where the scores would be accumulated and calculated, where ten yellow stars would represent full score and would be shown at top of the page. An arrow button would then be visible to subject to proceed to the next page which led to a rest page. Similar to the first study, this rest page would appear after every drawing task. There were 20 drawing tasks altogether for subject to complete the experiment. At the end of a session, a page with detail scoring for every drawing task and an overall score would be shown. The last page was a "thank you" page to subjects for their participation. The illustration on Figure 4.3 shows example of the procedure in completing the overall drawing tasks.

4.3.4 Experimental Design

Penalty Conditions			Medium Input	Order of Participant			Design
Close	Medium	Far	Finger	1	3	5	2 x 1
Close	Medium	Far	Pen	2	4	6	2 x 1

Figure 4.4: A mixed design experiment for Penalty Conditions and Medium Input.

The experiment was within participants design for penalty region(*close*, *medium* and *far*) and between participants design for drawing medium (*finger* or *pen*). There were two experimental groups; one group drawing with *finger* and the other drew using *pen*. All participants from both groups went through the same drawing tasks. It was a one data point per participant, a three-by-two analysis of whether subject's drawing action was affected by using the drawing medium inputs and whether it was affected by the penalty conditions. The drawing medium inputs and the penalty conditions are the independent variables while the number of stars as the scoring system is the dependent variables. The scoring system is determined by the nearest location of stroke points to the center of reward region. Details of how the distance of the stroke point being measured is explained in section 4.3.8. Figure 4.4 above shows the design layout of the experiment. The experiment lasted about 40 minutes to 1 hour per participant.

4.3.5 Subjects

There were 40 children participants (18 boys and 22 girls) with age ranging from 4 to 12 years old. Four children participants results were discarded from the analysis due to not following the order of the task, therefore, thirty six children participants were used with a mean age of 7.44 years (*SD*=2.5 years). There was a mixed background(nationalities/races) of children whom all attended nurseries and primary schools in Birmingham, UK. These children participants on average had two hours (per day) of tablets and touchscreen devices. Figure 4.6 shows the age distribution of the children participants.

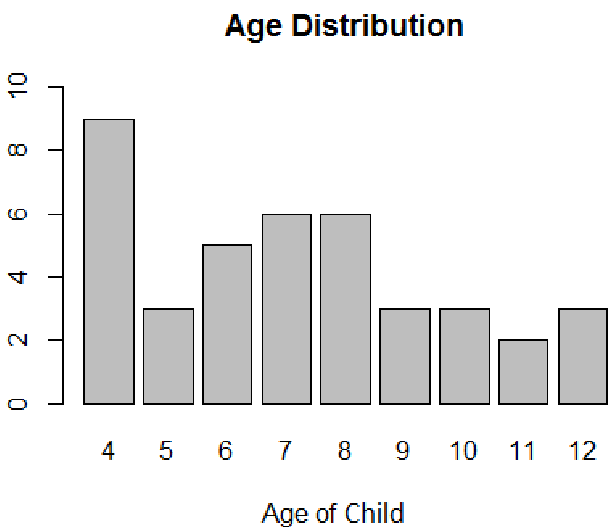


Figure 4.5: Age distribution for children participants in study 2.

4.3.6 Instruction

All parents had given their informed consent to allow their children to participate in the study in verbal and writing prior to their sessions. They were briefly informed on how the task would be run. Later, subjects had a warm-up session of joining the dots task on paper using a pen or a pencil. The purpose of this was to ensure that subjects were familiar with numbering order of 1 to 50. Once they had completed the task on paper, they were assigned to one of the two groups. The group assignment was based on the order of participants. The first subject assigned to group 1, *finger*; the second subject to group 2, *pen*; third subject back to group 1 and the pattern continued. All were unaware of the hypotheses of the tests. When subjects completed the task, they were each given a form to fill, sharing their background information and their exposure of drawing on paper and tablets. At end of the sessions, they were given a small gift bag as a token of appreciation.

4.3.7 Pilot Study

Pilot study was conducted on four children, two boys and two girls of age 5, 8 and 10. The pilot tests were repeated until all improvement and changes on the experiment design made. Improvements were made on the time limit to suit both young and old for children and the and also on the suitable distance between two dots.

4.3.8 Data Analysis

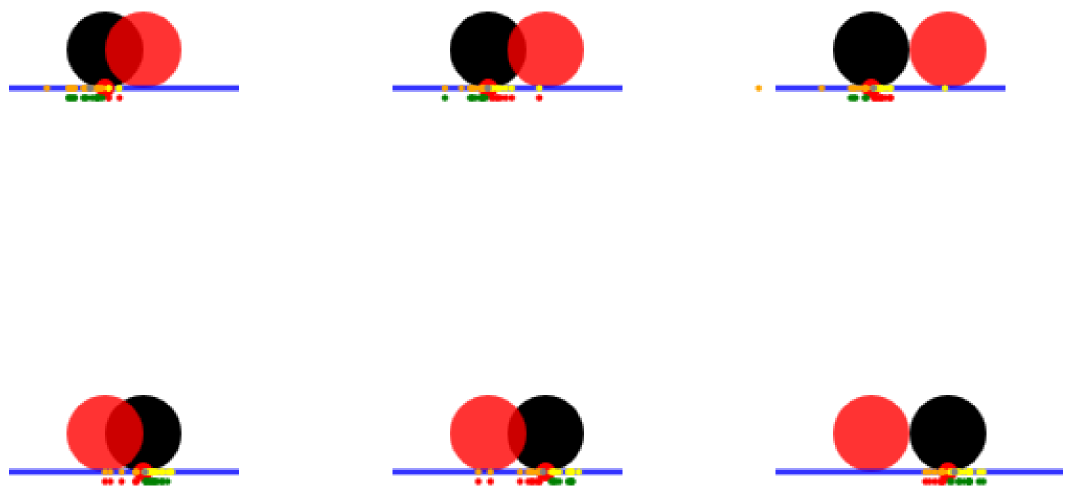


Figure 4.6: Example of end points distribution for left and right side of *close*, *medium* and *far* penalty regions from all the drawing tasks of subject 05. The orange data points on the boundary blue lines depicted the right side from the centre of reward region while the yellow data points depicted the left side from the centre of reward region. The grey color on the boundary blue line marks the centre of reward region. The green data points below the blue line show that the data points above it are awarded with a reward point within the time limit as opposed to the data points above the red data points, they are awarded with penalty or overlapped regions. Any data point on the blue line that does not have another data point colored below it shows that the particular data point had occurred after the time limit set.

There were 452 dots per subject for all the 20 drawing tasks and out of that number, 120 data points were dots of target and penalty region. Tasks that were completed beyond the time limit were omitted from the analysis. For each drawing, the *drawing time*, number of *stars* and the *endpoint* location of the drawing lines that reached the target areas were recorded. The normality of the continuous data were assessed and any noise that contributed to the faulty of the data was removed. This includes drawing lines that do not follow the order of the numbered dots and the drawing lines that go to other target regions rather than to their current targets.

Figure 4.6 shows orange and yellow tiny dots that lie on the blue lines as distributions of *end point* for all drawing task. The top three pairs of circles in Figure 4.6 are penalty regions placed on the right side of the target regions while the bottom pairs are penalty regions placed on the left side of target region. Below the blue lines are tiny dots marked in green and red in color with the green dots indicating that the dots above them (*end* *points*) are on the positive side of the target region while the red dots above them (*end points*) are on the negative side of the target region. Other dots on the blue line that do not have any green or red dots below them shows that the particular *end point* is discarded due to timeout. Since the *end points* are the final points in each drawing strokes that hit the perpendicular border of the target areas, only the x distances were needed in this study.

The drawing task in this current study has penalty region of higher point than the background, giving a prediction of the *aim point* maximizing expected gain to be shifted away from the centre but nearer towards the penalty region rather than the background. Since the score for non-overlapping target area was a five yellow stars, the score for penalty region was made one star while the score for background was zero.

Calculation for the End Point

The *endpoint* position (x_{ij}^{d}, y_{ij}^{d}) was recorded relative to the center of the target region for each proximity of penalty distance i(i=1,2,3), displacement condition j(j=1,...,6) and drawing task d(d=1,...,n_{ij}). The penalty distance were *close*(1), *medium*(2) and *far*(3). The displacement condition represented by the penalty region at the left or right side of target region. The unit distance of penalty regions from the target region are $x_{red,i}$=-0.5,-0.25,0,0,0.25,0.5 unit and $y_{red,i}$=0. The endpoint relative to the target center was calculated: $|x_{ij}| = X_{ij} - X_j^{target}$ in all conditions. The mean *end point* for each subject and each condition X_{ij} and Y_{ij} were averaged across replications $p = 1,...,n_{ij}$. A value of $| x_i | > 0$ indicated that the recorded *end point* was on the right side of the target center. Trials of the drawing task that were not within the time limit were omitted from the analysis. The *aim point* is the mean distribution for all *endpoints* based on the proximity of the penalty distances per subject. The normality of the continuous data were assessed prior to the analysis.

Predictions of Optimal Aim Point

The model predicts a shift of *aim point* in horizontal. Equation 4.3 is used to calculate the maximum expected gain for each penalty condition. According to Trommershäuser et al. (2003a) study, when the penalty region is zero, the *aim point* maximizing expected gain, ($X_{ij}^{meg}, Y_{ij}^{meg}$) is the center of target region, ($X_j^{target}, Y_j^{target}$) with ($X_{ij}^{meg} = X_j^{target}, Y_{ij}^{meg} = Y_j^{target}$). When the penalty is non-zero, the *aim point* maximizing expected gain shifts away from the penalty region and thereof, away from the center of the target region.

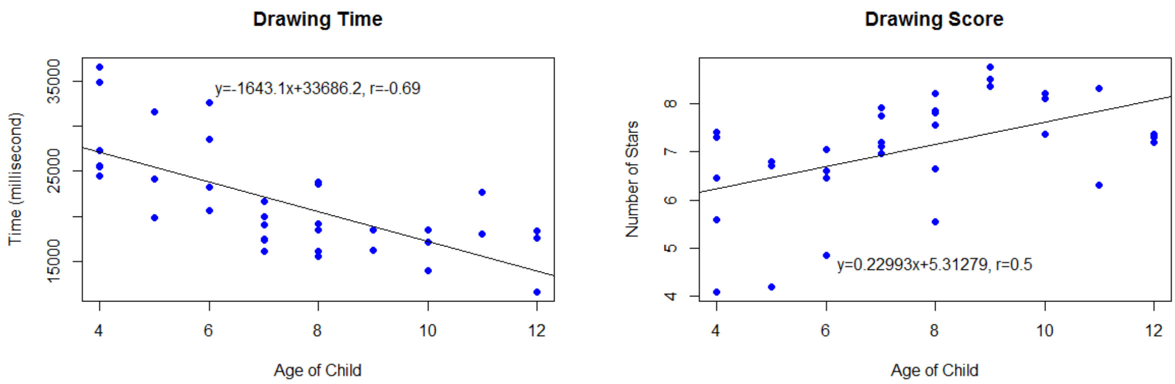
Predictions of Performance

To find subjects' individual score compared to optimal performance, the mean and variance distribution of optimal performance predicted by the model were computed. This was performed by a computer simulation for every penalty condition for each subject individually. The estimation of subjects' motor variance were simulated around 60 trials in each penalty conditions. This estimation was to see whether subjects' performance is significantly different from optimal.

Predictions of Efficiency

The efficiency is the comparison between subjects' performance and optimal performance. It is defined by taking the observed point as a percentage of optimal point. The observed point is the actual average score for a subject while the optimal point is the maximum expected gain calculated for that subject. The efficiency was also computed for each subject in each condition. From there, the average efficiency for all subjects was computed within all conditions to see whether subject's overall performance correlated with the optimal performance predictions.

4.4 Results



a: Drawing time. b: Drawing scores.

Figure 4.7: Drawing actions based on age distributions.

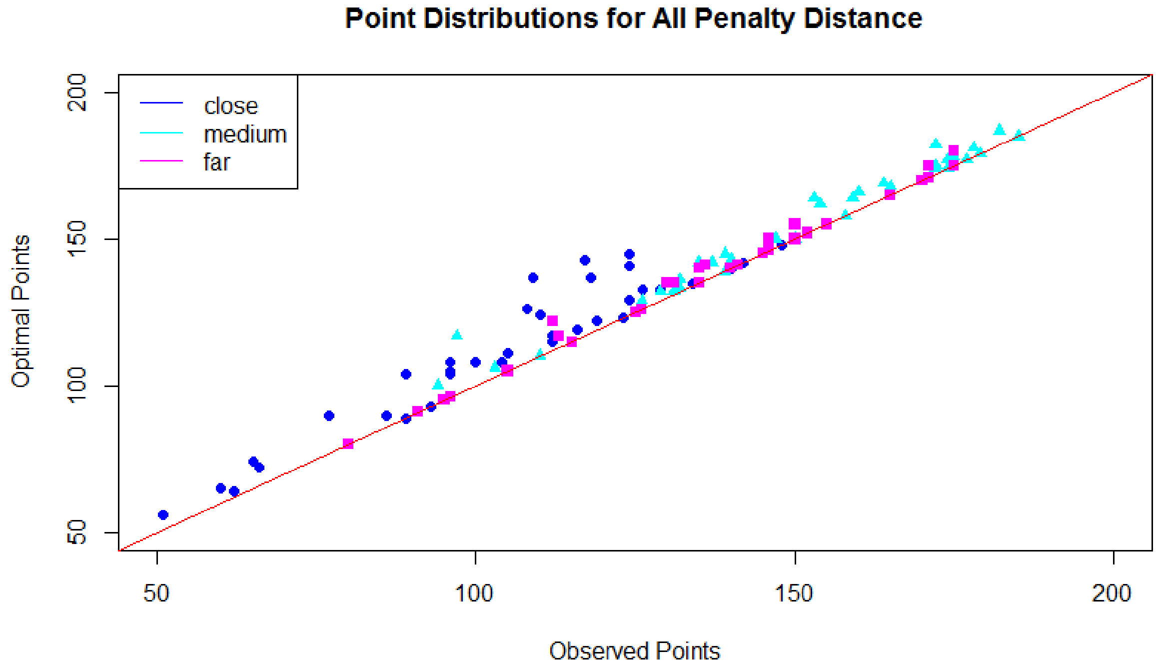


Figure 4.8: Observed and optimal points of all penalty conditions for all subjects.

In this second study, there were 36 children participants n=36 with 18 children participants in each group of medium drawing input, either using their finger or a pen. The relationship analyses were conducted using Pearson product-moment correlation coefficient. The result suggested that there was a strong significant negative correlation between age of participants with *drawing time*; r=-0.694, p<0.0001; indicating that younger child users spent more time to complete the tasks than older child users (see Figure 4.7a). There was a positive moderate significant correlation between age of participants with the number of *stars*; r=0.506, p=0.002; showing that older child users scored higher than younger child users (see Figure 4.7b).

Subjects were also found to alter their aiming points away from the penalty area in accordance to the model prediction. This is shown in Figure 4.9 where *aim points* in blue showed larger shift, *aim points* in cyan showed moderate shift and *aim points* in pink showed the least shift respectively according to the distance of penalty regions. My result is in agreement with the prediction where the main effect for the penalty conditions (*close*, *medium* and *far*) was statistically significant given $F(2,33)$=9.068 and p<0.0001. The main effect comparing the two groups for the medium drawing inputs (*finger* or *pen*) however was not statistically significant suggesting no differences due to the effectiveness of the two medium drawing inputs. There was also no interaction

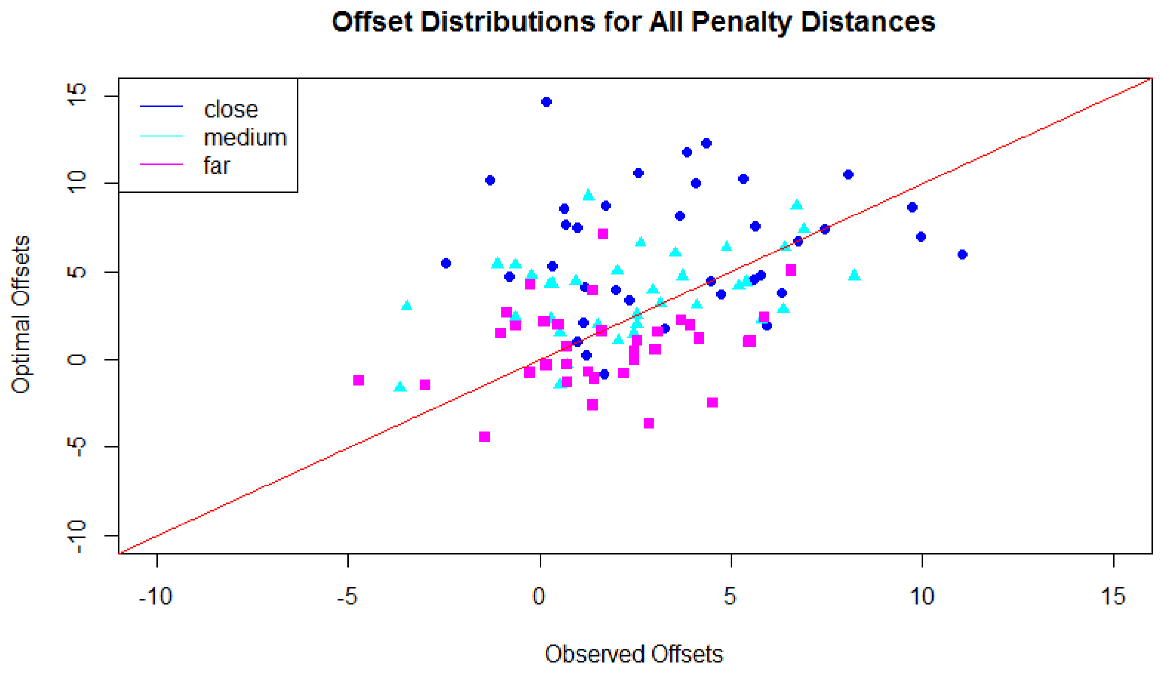


Figure 4.9: Observed and optimal offsets of all penalty conditions for all subjects.

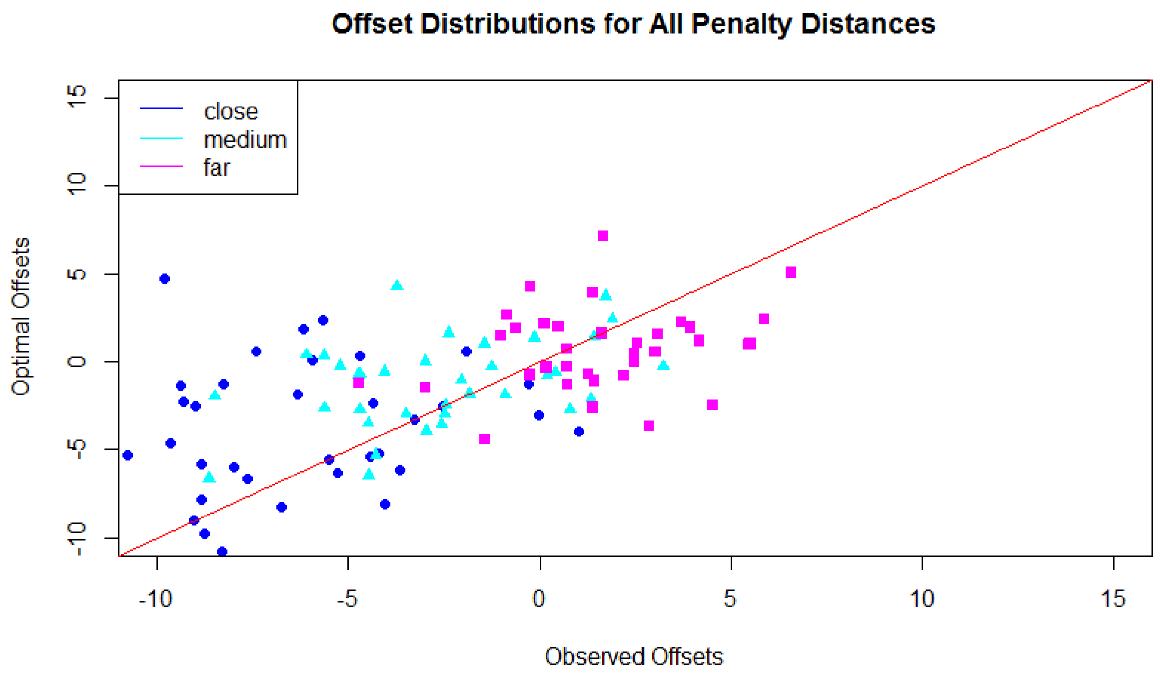


Figure 4.10: Observed and optimal offsets of all penalty conditions for all subjects relative to the centre of non-overlapping reward region.

effect between penalty conditions and medium of drawing groups. The performances of the subjects were examined in their drawing movement to see whether there was a gap from optimal performance. Figure 4.8 shows that there were strong positive significant correlations between the observed points and optimal points for all penalty conditions, $p<0.0001$ given close distance; $r=0.955$, medium distance; $r=0.988$ and far distance; $r=0.995$. The illustrated graph in Figure 4.8 shows that optimal strategy is a good predictor to participants' performance. All points shown in the graph are above the diagonal lines indicating that they could not go further than the optimal points. The overall mean efficiency of subjects' performance was 96.42% which is off by only 4% from the optimal performance resulting in a near-optimal drawing movement.

As shown in figure 4.9, the relative offsets for subjects' mean of *observed aim point* and *optimal aim points* were taken for all penalty conditions. The graph shows that there was a positive significant correlation between all *observed* and *optimal* offsets in all conditions given, $n=108$, $r=0.331$, $p<0.0001$; suggesting that subjects' aim points were close to the optimal *aim point*.

Figure 4.11 and 4.12 illustrated subject's *aimpoints* predicted at different offsets of margin 1 for each penalty conditions. The data from these subjects were chosen among all the subjects that made predicted shifts with highest number of data points. The drawing endpoints are distributed around this mean end point according to a bivariate Gaussian distribution. The colored bar lines in both Figures mark the region boundaries. The grey bar is the centre of the reward region and the dashed blue bar marked subject's observed *aim points*. Every *aim point* has a score that maximized the expected gain from all the possibilities regions. I made direct comparison of each subject's observed aim point with the predicted values x_{opt} of optimal aim point. The highest plot point in the graph is the optimal *aim point* having the highest score. While the aim point distributions of subject are seen to be skewed to the left, these are more apparent to penalty *close* and *medium* conditions. Referring to the graphs, subjects were seen to shifted their aim point away from the penalty regions according to their own motor variability. These are more apparent for penalty *close* and *medium* conditions rather than in *far* condition. When it is far, subjects seem to alter less.

Tables in Figure 4.13 show that 7 out of 18 subjects from Group A and 9 out of 18 subjects from Group B were making predicted shifts when drawing lines toward the target regions of different penalty conditions. The rest of the subjects were not making the predicted shift as expected.

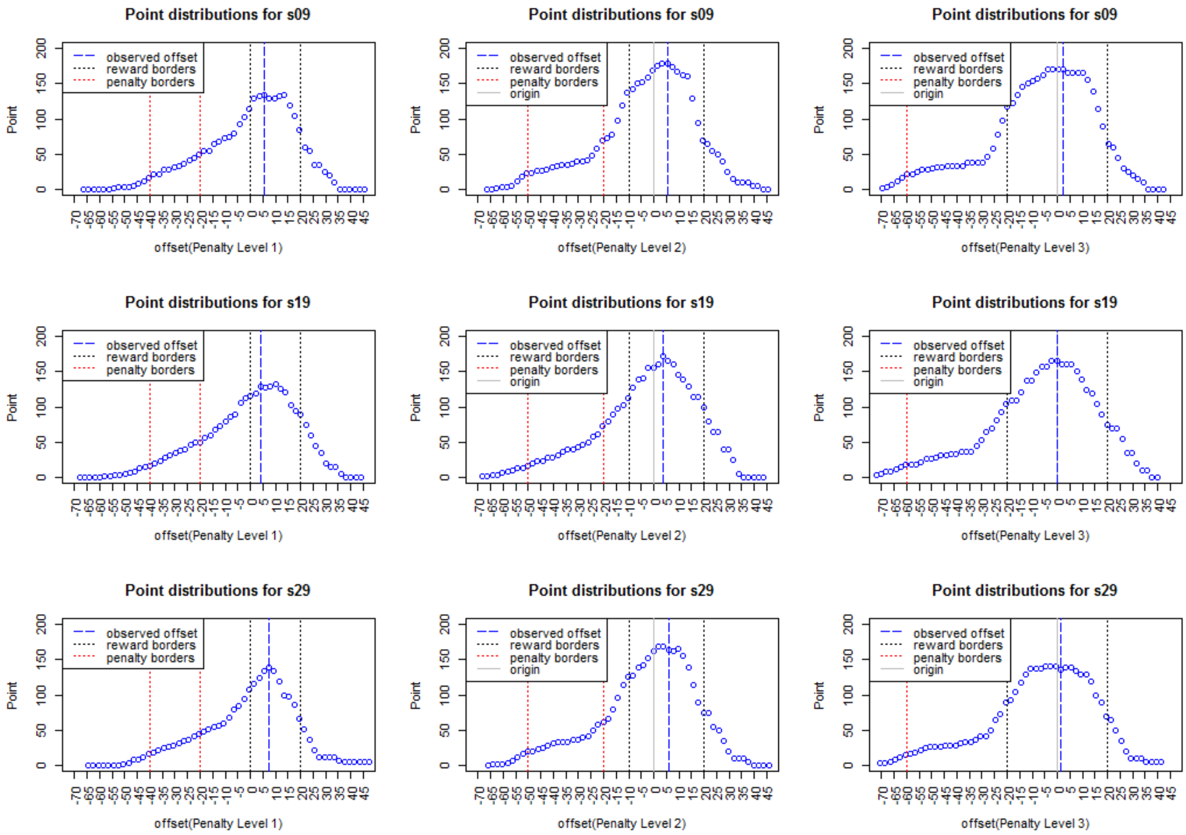


Figure 4.11: A direct comparison of observed aim points with the experimental data for subject s09, s19 and s29 (drawing using finger). The rows represent the subjects and the columns represent the penalty conditions for *close* (penalty level 1), *medium* (penalty level 2) and *far* (penalty level 3).

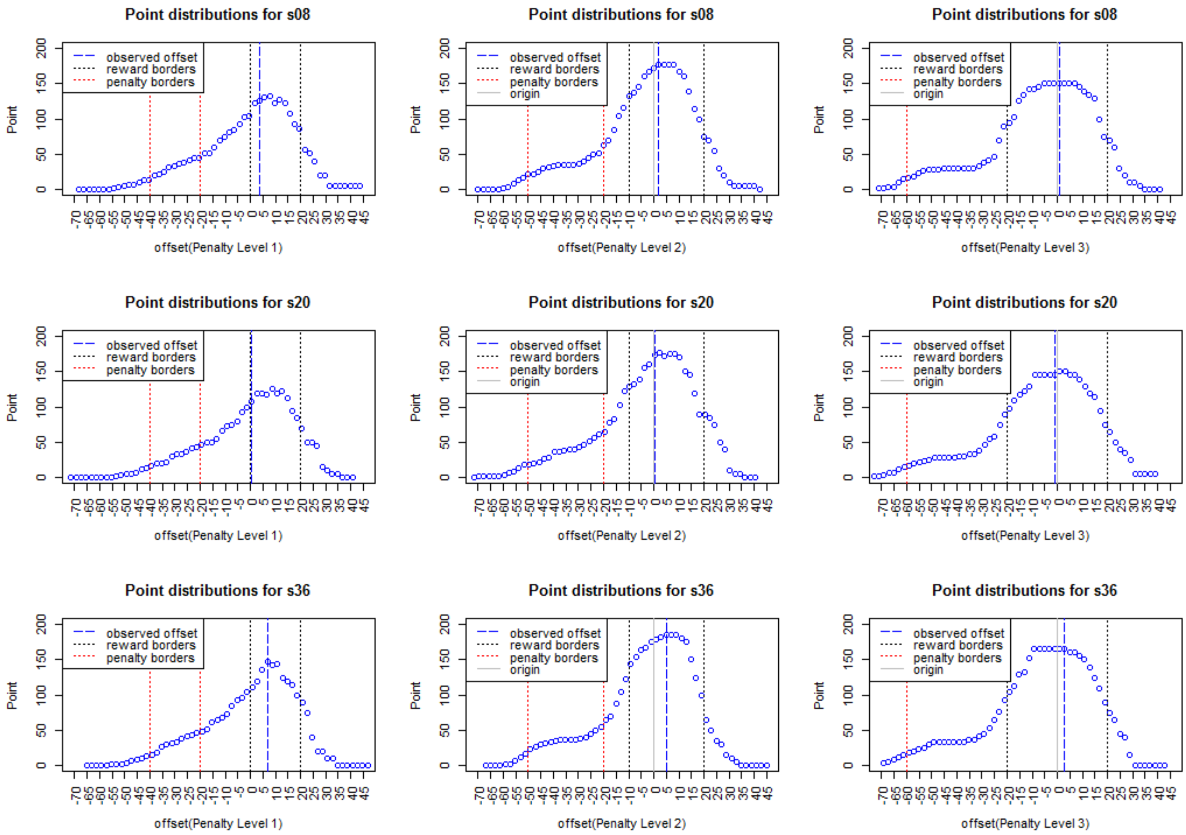


Figure 4.12: A direct comparison of observed aim points with the experimental data for subject s08, s20 and s36 (drawing using pen). The rows represent the subjects and the columns represent the penalty conditions for *close* (penalty level 1), *medium* (penalty level 2) and *far* (penalty level 3).

Subjects	Penalty Distance		
	Close	Medium	Far
A01	0.979112372	2.191549878	-4.717652536
A03	4.050705045	2.459778353	0.134630886
A05	4.473588013	-0.223469068	1.416909076
A07	5.632099479	5.043950952	5.466674139
A09	5.580710529	5.405764209	2.199090136
A11	3.617760288	2.496095843	4.089738036
A13	5.942863533	1.270279082	-2.979825262
A15	-1.316565802	-0.640837174	0.162570659
A17	0.691402025	0.51312204	-0.629537043
A19	4.061009362	3.731960135	-0.253167084
A21	0.189687855	-1.099768971	1.609457128
A23	10.58243805	6.717710121	5.509793861
A27	2.251347428	3.111114177	6.012043443
A29	7.452540296	5.794254034	1.39907675
A31	1.150946243	3.168978131	4.523700604
A35	6.330036101	0.267608744	2.470460519
A37	3.339971292	0.316030485	1.392923996
A39	8.081345862	8.221945002	3.949971188
Average	**4.060610998**	**2.708114776**	**1.764269916**

a: Aim Points for Group A.

Subjects	Penalty Distance		
	Close	Medium	Far
B02	1.161175599	-3.647823966	0.477917983
B04	1.732096448	2.443594611	1.653162376
B06	0.333671833	-0.649953701	1.269960093
B08	3.667368113	2.016746658	0.710231361
B10	1.689101736	6.350423469	2.550601707
B12	6.800382307	2.765307196	3.916376717
B14	9.711757787	6.402234036	3.034650136
B16	5.795270665	2.540014737	2.469819489
B18	1.990668776	1.509859708	0.721640747
B20	0.621576774	0.291726877	-1.012318522
B22	-0.790554234	0.937061658	-0.861163459
B24	5.316142559	5.194242075	0.711933288
B26	1.217405955	0.703706715	-0.245704924
B30	0.991416017	2.951579252	-1.444002202
B32	9.974698114	6.893934334	3.721341174
B34	2.58889279	0.526668993	3.090920531
B36	6.732905194	4.874278021	2.850689063
B40	-2.476794642	-3.482559989	0.173554921
Average	**3.169843433**	**2.145613371**	**1.321645027**

b: Aim Points for Group B.

Figure 4.13: The aim points of penalty conditions for group A (drawing using *finger*) and group B (drawing using *pen*).

4.5 Discussion

The result suggested that subjects were making predicted shift based on the prediction model but how do I know whether subjects were truly making optimal adaptation? Perhaps the subjects were aiming what was left at the middle of the targets if in the case they were adapting less. Would this suggest that subjects were aiming at the centre of the non-overlapping reward regions, rather than optimising? To investigate this further, I made an additional analysis to define subjects' *aim points* relative to the centre of non-overlapping target regions. I plotted the optimal *aim points* versus observed *aim points* for all penalty conditions relative to the centre of non-overlapping reward region (see Figure 4.10). Although the graph shows a weak positive non significant correlation given r=0.292, p=0.08; the overall scatterplots do not revolved around the centre of non-overlapping reward regions but rather, are shifted away from the centre of non-overlapping reward regions. However, since the penalty region has higher value than the background, as mentioned earlier, the scatterplots seem to shift near towards the penalty region rather than the background. Therefore, in response to the question: *Weren't subjects were just aiming at the centre?* In the analysis, displayed in Figure 4.10; it is shown that this is not the case. Subjects showing near optimal adaptation offers a better explanation.

Overall, the subjects were actually found to be making near optimal adaptation. The next question to be answered is, *does adaptation to motor variability explain age-related* *changes in drawing performance*? From the analysis of the current experimental work, the study reported that there were no significant correlations between age of participants to motor variances. This shows that adaptation to motor variability is not according to age-related changes of drawing performance. Similar to Study 1, the current study did not show any significant difference in the medium of drawing input, drawing using pen and finger. Given that there is a penalty effect in Study 2 that distinguished the design of the current study to Study 1, the manipulation of the input method (pen/finger) is remained, to test if there is an effect on the scoring or drawing performance. The result showing that there was still no effect on the input method could be due to the nature of the task itself. Differences in the drawing performance maybe clearly seen if the task was to test on different directions or details of a drawing shape. The current study in overall was testing on how user draw the overall lines of a figure.

4.6 Limitations

A wide topic in the literature review discussed about children developmental growth from the psychological perspective of drawing system as explained in chapter 2 in section 2.4 of Background and Theoretical Framework. In contrast, the result of this study did not show any correlation of motor variance to age related changes in terms of the drawing performance. Looking closer at the result of the study, almost half of children participants did not follow the prediction of the model. While this may reflect naturally how children react to the drawing task, they could also probably were not performing well. The task may be far more challenging than they anticipated. Trommershäuser et al. (2003b) work use a single target in their ballistic aiming pointing task. Due to the nature of join the dots task, this study had to use more than one target in one drawing task. This makes the drawing tasks harder than the adult pointing task of Trommershäuser et al. (2003b) work. Child users made mistakes mostly by drawing the lines in out of order. This could be due to a few reasons. From the experiment done, when the drawing figure formed from the dots presented in a single task became more apparent, some child users predicted the image of the picture and informed it verbally to the experimenter. Children tend to plan their drawing before attempting it by talking first most of the time before they draw to organize and plan their drawing movement (Stetsenko, 1995). This influenced how children proceed in completing the drawing tasks which in the current study; by not following the numbering order. According to Van Sommers (1995), when a person developed their own way of portraying things, the developing skill is based on a visual record of ones practical action. Where they start the drawing, how they progress in the direction of drawing and the strategies adopted is already established. This leads to a bias drawing performance which leads to drawing through the dots but in out of order. On a different note, Gori et al. (2008) reported that young children could not integrate optimally in both visual and haptic cue at the same time. If this is the case, having more than one target presented at the same page of one drawing task; in a continuous interaction manner, would be above than children's own capability. This may explain why most children in the experiment were not adapting well. Also, as there were several target circles present in one single task, the target circles sizes had to be limited to small sizes. This could be hard for a child to aim their drawing strokes on a target especially when under time pressure. According to Anthony et al. (2012), children showed higher miss rate when attempting smaller targets compared to larger targets. This can lead to more errors in the motor noise during interaction. Target used in Fitt's law model also showed predictive performance dropped when the targets were small (Chapuis & Dragicevic, 2011).

The current explanation concluded that there were limitations in the ecology of the task. This can affect the behaviour mechanism of children's drawing actions. Therefore, the ecology of the task needs to be revisited and improved thereupon to overcome any limitation and weaknesses in the current study. What constitute to the capacity of childen's mechanism of drawing behaviour should also be considered. An improved version of the current drawing task is needed to strengthened the result of the current study. This is explained in the next chapter of the third study.

CHAPTER 5

STUDY 3: DRAWING AND CALIBRATION PROCESS

5.1 Introduction

This chapter describes the third study of children's drawing task an improvement to the second study with improvement on the ecology component of the task. This study shared the same goal with the previous study. Due to the difficulties imposed from the design of the second study, not all children in the experiment were able to perform the task very well. Improvements were made to avoid any biases and difficulties during interaction. Changes were made on the stimulus configuration where; instead of having several targets in one single task, a one to one intervention was used. Hence, there would be only one target with reward and penalty effects at one time within a time constraint. This design followed closely Trommershäuser et al. (2003b) work. Other targets were removed to avoid unnecessary intervention during interaction, which helped to reduce errors in the motor noise during movements. This help children participants to focus solely on the current target.

Another change adopted was by changing the shape of the target, from a circular shape to a semi-circular shape. In the previous study, the end point of the strokes, which was used for the main analysis work, was extracted from user strokes that hit the boundary line of the circular shape (see Figure 4.6). This end point did not reflect the end point that hit the target of reward and penalty regions, thus exhibiting less accuracy and unreliable data. Therefore, the current study requires a change to a semicircular shape as the target region in the drawing task. When a child user draw a line towards a target area, the single point that hit the boundary of the actual target is extracted from user strokes. This is more accurate and gives a reliable data for analysis purposes.

In order to solve the problem of small target size in the previous study, a visuo-motor calibration procedure for finding an ideal target size was introduced in the current study. In the early phase of the experiment, children need to draw a line towards a target area with only the reward function active, within a time constraint. After several set of trials drawing, the right target size will be acquired suiting to the child motor response according to a certain error rate. This was done using an adaptive method of psychometric function (Wichmann & Hill, 2001).

With the changes and improvements made on the ecology of the drawing task, children would be able to adapt better according to their own mechanism when performing the drawing task. The ecology of the task was strengthened to answer the research questions as mentioned in section 2.6. The next section explains the adaptive procedure in brief.

5.2 Visuo motor calibration

Visuo-motor calibration per se, is a process of maintaining an appropriate mapping between visual estimation and motor control that requires continual updating. The adaptive method provides human performance rate that depends critically on previous responses of a sensory task. The process can gradually help to reduce errors from a motor noise for the accuracy of a performance to be improved (Burge et al., 2008). Contreras-Vidal et al. (2005) work uses the same procedure to children from 4 to 8 years of age, to investigate how their hand movement developed when drawing. Their study shows that older children were found to make faster, smoother and straighter line drawings while younger children would require more experience and time to develop and reach the same level. Therefore, due to poor stability and precision of targeted movements in young children (Jansen-Osmann et al., 2002), this study used a visuo-motor calibration procedure to find a good target size that suits the children in the drawing tasks. Gepshtein et al. (2005) work has proven that, when there is a size discrimination of a target, with visual and haptics signals spatially coincident, the performance in the interaction was statistically indistinguishable to optimal. This strongly suggested that a calibration method of size discrimination to avoid errors in the motor noise of the current study is vital to strengthened the results claimed. The next paragraph briefly explains how the adaptive method works using a psychometric function.

Over the years there have been many adaptive methods (e.g., Levitt, 1971; Watson & Pelli, 1983; King-Smith et al., 1994; Wichmann & Hill, 2001) that were developed to understand and obtain accurate information of subjects behaviour in a psychophysical task.

The performance of a subject is typically summarized by reporting one or more response thresholds. A given level of performance is defined by a stimulus intensity. If the stimulus intensity increased along with the improvement of performance, a characterization rate and all other measures are fed into the psychometric function. This psychometric function describes the dependence of a subjects performance to a physical aspect of the experimental stimulus. It is a mathematical function relating the probability of correct responding to the physical variable of experimental work. It is used to compare the thresholds obtained with a 75% correct criterion. The slope of the function can also be used to examine the steepness of the psychometric function that measures the reliability of the sensory performance. The method is explained in detail by Wichmann & Hill (2001). This method is used on a target size discrimination to improve the accuracy of children's rapid drawing movement on a touch screen surface.

5.3 Method

5.3.1 Apparatus

Refer to section 3.4.1.

5.3.2 Stimulus

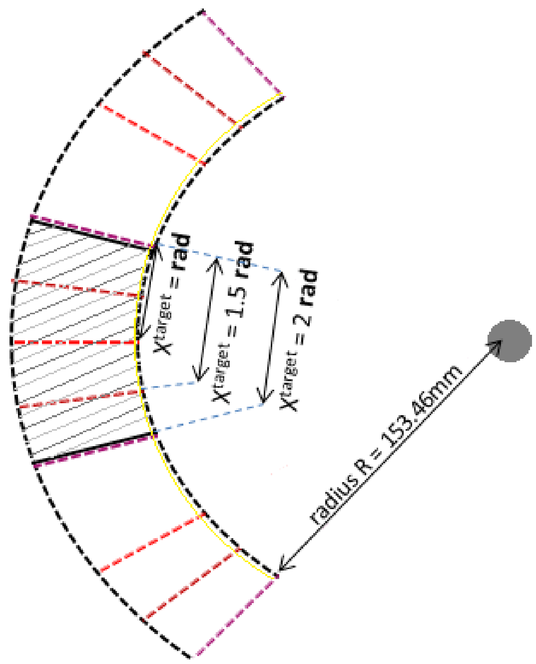


Figure 5.1: The target and penalty region motivated by Trommershauser et al., 2003.

There were 7 drawing tasks in one set of trial drawings which is done in the first session. Each of the trial drawing tasks consisted of a small grey circle as starting position for subject to draw a line towards a semi circular shape as that acts as the target area. Figure 5.1 shows a target area with black stripes and three other penalty regions in different distances to the target area at the upper and lower side of target area. Two dashed lines with the same red colour represent one penalty region. The red shades mark the boundaries of the penalty regions. The penalty region and the target region are equal in size and their size was determined by the calibration process in the first session. The target size was chosen from the calibration process of the first session. Both reward and penalty regions were semi-circular shapes with one side of the circumference edge in bright yellow. The yellow line marks where user drawing line is hit to the target area.

A set of trial drawings had one consistent size of target area that was placed randomly in terms of angle and position for 7 times. The distance between the starting grey circle and the target area was kept at a constant distance of 580 pixels/153.46mm. The small grey circle has a radius of 30 pixels/7.94mm. During the set of trial drawings, the target area appeared in seven different sizes, starting with the middle size (size four). Example of different target sizes can be seen in Figure 5.3c, 5.3f and 5.3h.

In the second session, where the real data was gathered, the reward region were colored in black while the penalty areas were colored in red. The reward and penalty regions were randomly located in each of the drawing tasks in this session. Both of these regions as a target area had angle ranging from 155 to 205 degree at left side of the small grey circle and 340 to 360 degrees or 0 to 20 degrees at the right side of the small grey circle. The rest of the other angles do not fit the screen area (see Figure 5.2).

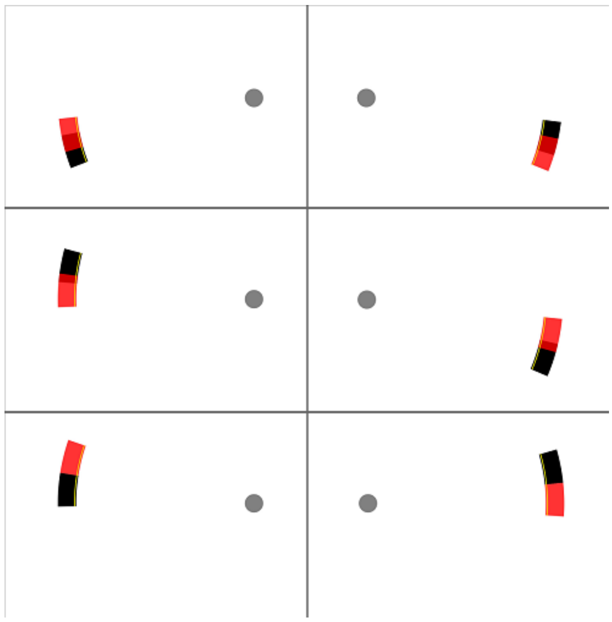


Figure 5.2: Penalty displacement used in the second phase of drawing application. The black area (non-overlapping reward region) gives 6 stars, the red area (non-overlapping penalty region) gives 1 star, the maroon area (overlapping reward and penalty region) gives 3 stars and background area (outside) gives 0 star.

5.3.3 Procedure

a: Front page.

b: Instruction page.

c: Drawing task 1 started with the middle size target region (Size 4).

d: Time-out score if drawing performed is out of time limit.

e: Overall score for one block trial of 6 drawing tasks with the same target size.

f: The largest target size (Size 7).

g: A reward score for drawing the line within time.

h: The smallest target size (Size 1).

i: Final score for calibration session. A target size has been identified.

Figure 5.3: Drawing application *Draw-a-line*.

The experiment started with a 20 minutes calibration session to determine the ideal target size area using a psychometric function. Here, a subject would be required to draw a straight line from a grey starting point to the target area. The main session was about 40 minutes of drawing task with target and penalty regions included.

In the first session, subject needed to place their finger to draw at the small grey circle. Each drawing task only started when the subject placed his or her finger on the grey starting point. The drawing time began when the line stroke passed through the circumference of the small grey circle and ended when the line stroke touched the target area. If the drawing line reached the targeted area within the constraint time, five yellow stars would be displayed in the middle of the screen. For a task that is completed after 500ms, no gold stars would be shown. A set of drawing trials consisted of 7 drawing tasks. Each subject are scored to a maximum of seven stars as the full score. The same set of trial drawings were repeated but with different target size. Each subject are scored to a maximum of seven stars as the full score until an ideal target size was found that fit the criterion of a specified error rate. The first session ended when the ideal target size was determined and the subjects were given a short break before the second session started.

The second session was the main part of the experiment and it was similar to the first session but with penalty regions included with a fixed target size. The second or main session was started with subjects given 12 practice drawings and the scores for these drawings were not counted towards the final score. The practice drawings had 12 stimulus configuration with all possibilities included such as all three penalty distances placed to either upper or lower of target area and to both left and right sides of the screen. This was to ensure subjects were familiar with every possible penalty conditions. This was followed by 19 sets of drawings with each set containing 12 drawings each. The sets were separated by a rest page to help subjects maintain their focus. In this second session, subjects were required to draw a line towards the target area within the given time. If the subjects line stroke touched the non-overlapping reward region in time, six golden stars would be displayed. If it touched within the area of the non-overlapping penalty region, only one golden star would be displayed. If the drawing stroke touched the overlapping region of the target and penalty areas, three golden stars would be awarded. Subjects were encouraged to finish all the drawing sets but they can also stop after the 12th or 15th sets if needed. The drawing data was readily recorded after each sets. Figure 5.3 shows the sequence of drawing task of the first or the calibration session. The main session was similar but with a penalty region placed together. The experiment lasted about 40 minutes to 1 hour per subject.

5.3.4 Experimental Design

The experiment was within participants design for independent variables: penalty region (*close*, *medium* and *far*). There was only one experimental group where all subjects were required to use their finger-tips to perform the drawing task on a touch screen tablet device. It was a one data point per participant, a one-by-three analysis of whether subject's drawing action was affected by the three conditions of penalty distance.

5.3.5 Subjects

There were twenty children participants (15 boys and 5 girls) with age ranging from 5 to 11 years old with a mean age of 7.65 years (*SD*=2.1 years). There were a mix background of children whom all attend primary schools in Birmingham, UK. Figure 5.4 shows the age distribution of children participants.

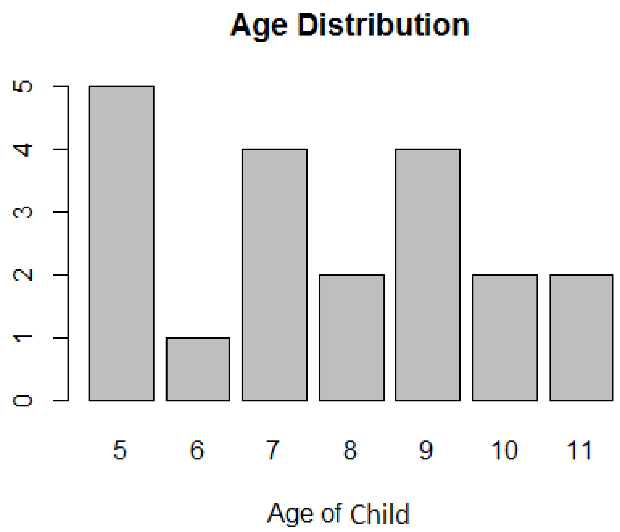


Figure 5.4: Age distribution for children participants in study 3.

5.3.6 Instruction

All parents and children participants had given their informed consent to participate in the experiment similar to how previous studies were conducted. Subjects were informed the payoffs and penalties for each penalty condition. All were unaware of the hypotheses under tests. Subjects underwent two sessions which were the calibration session and the main drawing task session. Since this was a repetitive drawing task, only few children did not completed all set of trials where they decided to stop at trial 12th and 15th. The data for all subjects were included in the analysis irrespective of number of trials completed. At the end of the sessions, subjects received a small gift as token of appreciation for their participation.

5.3.7 Pilot Study

Pilot study was conducted to four children, two boys and two girls of age 5, 8 and 10. The smallest target size was too small, therefore the target sizes were made larger into two units for all the sizes in the calibration session to conveniently fit child users little fingers.

5.3.8 Data Analysis

In terms of data recorded, in the first session, only the target size was recorded. In the second session, the drawing time, the end point (x,y) that hit the circumference area at the end of the radius and the score for every trial were recorded. There were 228 data points per subject in 19 set of trials. One set of trials consisted of 12 drawing tasks where six stimulus configurations were Right-to-Left directions and another six were Left-to-Right directions. The *end point* that hits the yellow entrance line is calculated in degree (angle) from the small grey circle. The calculation for *end point* and predictions of optimal *aim point*, performance and efficiency should be referred to section 4.3.8.

5.4 Result

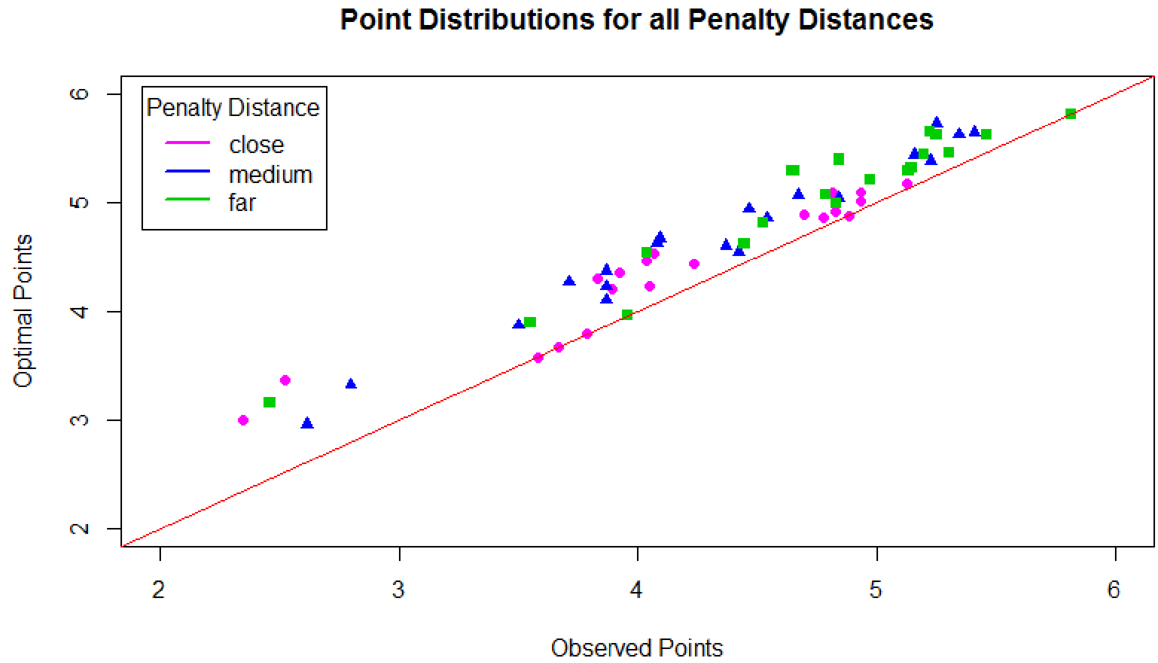


Figure 5.5: The observed and optimal points of all penalty distance for all subjects.

There were n=20 data participants. For the adaptive method of calibration procedure, the result of the study suggested that there was no significant correlation between age of child to target size.

The result suggested that subjects altered their aim point away from the penalty area according to the model prediction. The model predicts that when there is a penalty region closer to the reward region, subjects make a large shift on their aim point away from the reward region and when the penalty region is far away from the reward region, subjects make a small shift away from the reward region. The result is in agreement to the predicted shift. This is shown in Figure 5.6 where aim points in pink showed larger shift, aim points in blue showed moderate shift and aim points in green showed the least shift respective to the distance of penalty regions. The result was statistically significant by Wilks' Lambda = 0.1, $F(2{,}18) = 81.226$ and $p<0.0001$ with multivariate partial eta squared = 0.90. In addition, the aim points for all penalty conditions in both direction; Right-to-Left and Left-to-Right were analyzed to see if there was an effect in the direction of interaction. No interaction effect was found between both directions.

Figure 5.6 shows the observed and optimal aim points for all subjects in the three

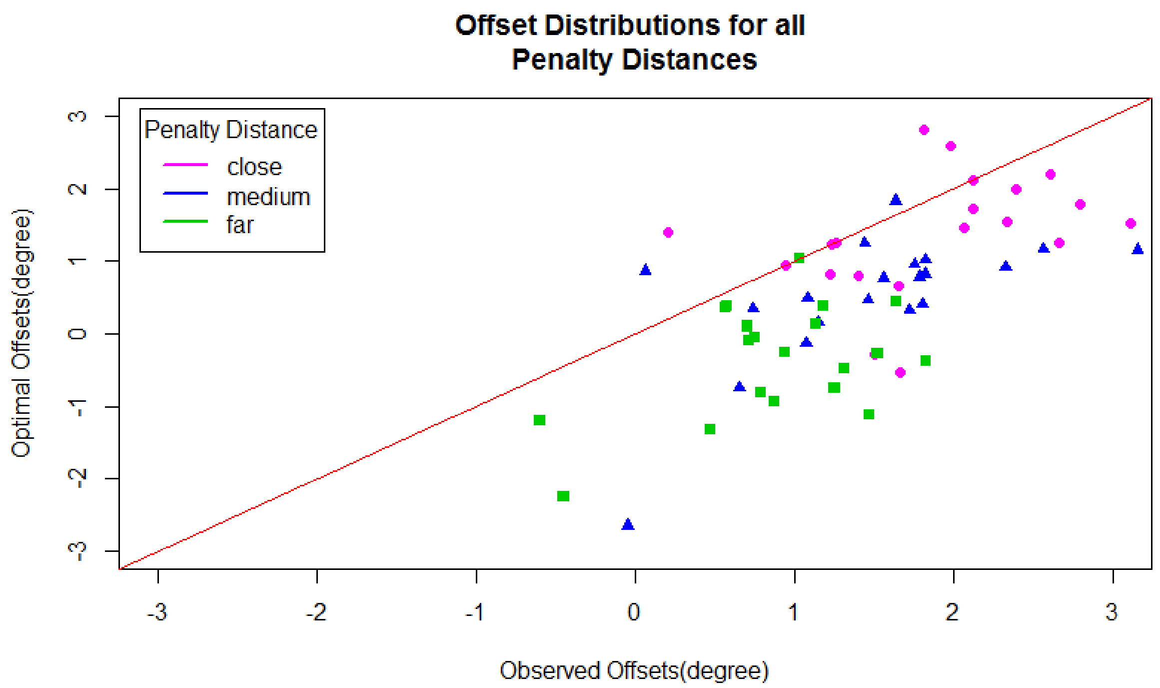


Figure 5.6: The observed and optimal offsets of all penalty distance for all subjects.

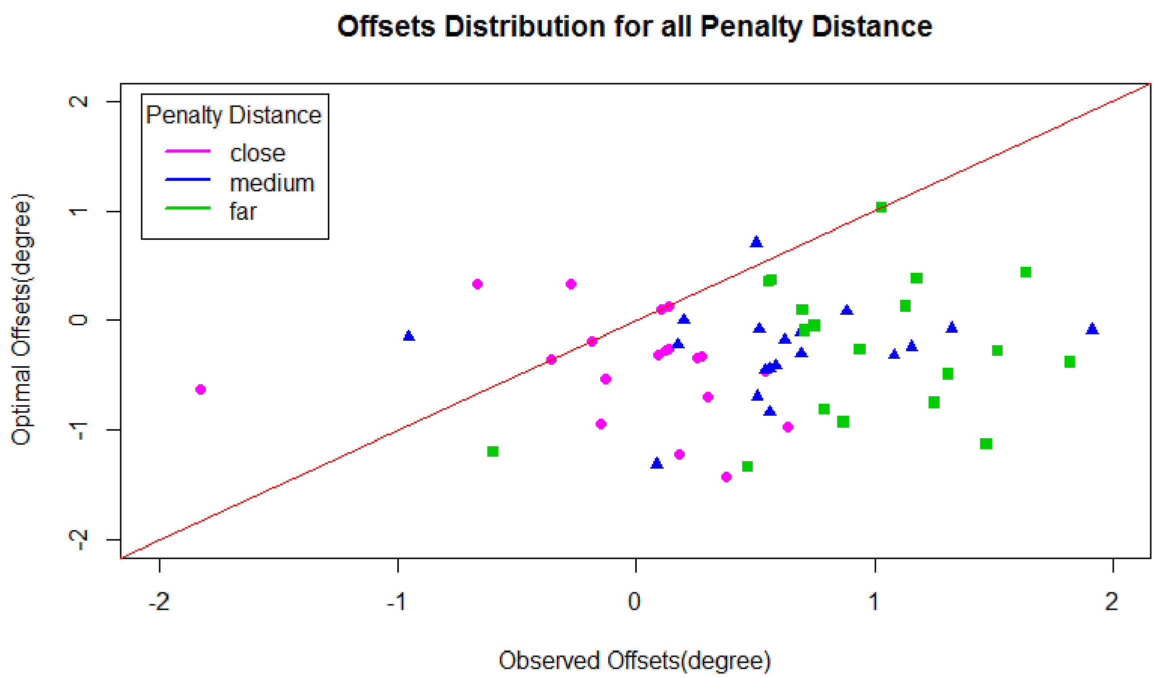


Figure 5.7: The observed and optimal offsets relative to the centre of non-overlapping reward region

penalty conditions. Most of the aim points in the graph are below the diagonal line due to the distance of observed aim points larger than the distance of optimal aim points respective to the penalty region. The optimal aim points were not far away from the penalty region as predicted because of its value having positive number than the background. From the data collected, I could examine whether subjects observed aim points were almost optimal or not. The graph shows that there was a strong positive significant correlation between optimal offsets and observed offsets for all subjects in all conditions; $p<0.0001$ with *close* distance $r = 0.96$, *medium* distance $r = 0.985$ and *far* distance $r = 0.964$. The result suggested that subjects' aim point were close to the optimal aim points. All points shown in Figure 5.5 are above the diagonal lines as they could not go further than the optimal points. The efficiency of subjects' performance was 93% which deviate less than 7% compared to optimal performance.

To find out whether there was a difference between subject's performance and optimal performance, the optimal offset given subject's individual motor variance was determined, shown in Figure 5.10. The highest point in each figure marks the optimal performance while the blue dashed lines marks subject's performance. Subjects' performance in drawing movement were examined to see whether there was a gap from optimal performance. The result stated that there was a main effect in observed and optimal performance for all penalty conditions with observed performance having $F(2,38)=32.901$, $p<0.0001$ and optimal performance having $F(1,19)=106.318$, $p<0.0001$. There was no interaction effect between the two showing that the two were not distinguish to one another. Figure 5.5 shows that there was a strong positive correlation between the observed points and optimal points for all penalty conditions with $p<0.0001$ for *close*; $r = 0.983$, *medium*; $r = 0.991$ and *far*; $r = 0.986$. This suggests that the optimal strategy is a good predictor to participants' performance.

To understand how observed and optimal aim points were obtained for each subject, an example illustration of the data in Figure 5.8 is shown. A direct comparison of the prediction values x_{opt} was made in this figure. The drawing movement endpoints are distributed around this mean end point according to a bi-variate Gaussian distribution. The experimental data was simulated for every subject in every penalty conditions using equation 4.3 to find the aim points for every offset of margin 0.2. The colored lines marked the bars for all boundary regions; reward, overlapped, penalty and outside regions. The grey bar indicates the centre of the reward region and the dashed blue bar marked subject's aim point, which is the observed aim point. Every aim point had a point score which maximized the expected gain from all of possibility regions. The highest plot point is the optimal aim point that shows highest score. The aim point distributions are more normally distributed for penalty region *far* condition. Other graphs are showing slightly skewed-left. The variance of these aim points show that children adapt their drawing actions according to their own motor variability.

To find out whether subjects were aiming at the centre of non-overlapping reward region, rather than optimizing or whether they were truly making optimal adaptation, an additional analysis to cater subjects' aiming points relative to the centre of non-overlapping target region was conducted. The optimal aiming points versus observed aim points were plotted for all penalty conditions as shown in Figure 5.7. From this figure, the scatter-plots do not revolve around the centre of non-overlapping reward region. The optimal aim points are shifted towards the penalty region because the points are higher on the penalty region compared to background. The observed aim points are shifted towards the background. Children participants may rather alter their aiming point away from the red penalty region although the point of the background was higher. To find the relationship of observed and optimal aim points for all penalty conditions for each subject, the mean of observed and optimal aim points were computed in all conditions per subject to get the correlations from the pooled data. The result suggested that there is a medium positive significant correlation between the mean observed and optimal aim points with $r = 0.460$ and $p<0.005$. In response to the question: *Isn't that subjects were aiming at the centre?*. The analysis displayed in Figure 5.7, shows that subjects were making near optimal adaptation.

Does adaptation to motor variability explain age-related changes in performance? In the previous study, this was not the case. For this study, the result has shown that there were strong negative significant correlations between age of children and their motor variance. The correlation between age of child and motor variance for penalty distance *close* is r=-0.643, $p<0.005$; *medium* is r=-0.628, $p<0.005$; *far* is r=-0.587, $p<0.05$ and the average of all penalty distances is r=-0.634, $p<0.005$. Does adaptation to motor variability explain age-related changes in performances? Figure 5.9 offers the answer.

5.5 Discussion

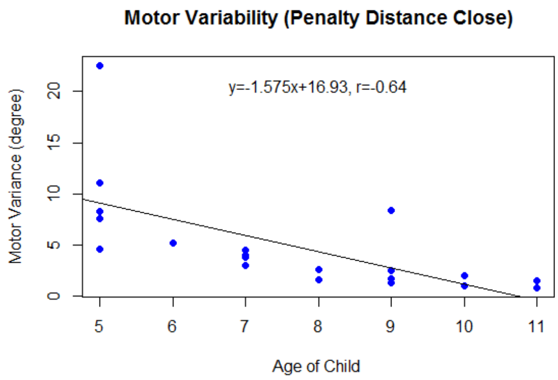
The study aimed to investigate how every child user responds to the reward and penalty effects of the drawing task in a one to one intervention. The design of the drawing task is closer to the ballistic aim point movement of Trommershäuser et al. (2003b) work. The model of movement planning in section 4.2.1 was used for the analysis in this study. In the previous of the second study, although children participant were showing near

Penalty Distance			
Subjects	**Close**	**Medium**	**Far**
1	1.667612115	1.085265566	0.526407059
2	2.833379046	2.1694725	0.985161074
3	1.811858762	0.280600182	0.072632833
4	2.999729261	1.668401162	0.440899716
5	3.156761708	1.683284856	0.07395261
6	3.352801145	2.148300217	1.800168404
7	2.529617353	1.774333931	0.788320825
8	2.62975938	1.944303316	1.145154554
9	2.62823853	1.523121938	0.50157635
10	1.495328536	1.030503133	0.578035426
11	1.997289772	0.717463798	0.935728973
12	2.7144979	1.903853666	0.798425187
13	1.652184695	0.944469623	0.697733817
14	1.301017064	0.742886806	0.448772171
15	0.583622764	-0.42440322	-0.491839218
16	2.444713414	1.465513828	0.520545194
17	3.084304111	2.057094264	1.288640674
18	1.335059676	0.55368853	0.466969893
19	2.041289948	1.473827491	0.805856112
20	3.782903898	2.159840791	1.44652773
Average	**2.302098454**	**1.345091119**	**0.691483469**

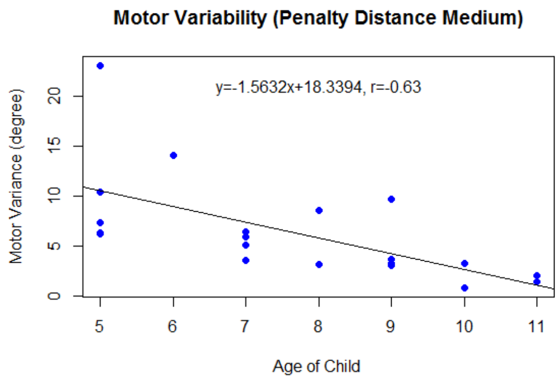
Figure 5.8: The aim points of penalty conditions for all subjects.

optimal adaptation, there was no correlation on the age related changes to the adaptation of drawing performance. The previous study have limitations where there were too many targets in one drawing task and that the target size was smaller. Therefore, the current study has tackled these issues by improving the stimulus configuration to a one to one intervention. According to Fitts (1954), subject compensates drawing movement to reach the acquired target if the target size is smaller. This could be more difficult for a child user to adapt given a strict time set compared to adult. Therefore, prior to the main session of the drawing tasks, an adaptive method of visuo-motor calibration is conducted to find the ideal target size for each child user. Size discrimination of a target in an interaction can improve the accuracy of the movements. This is supported by Gepshtein et al. (2005). Hence, the adaptive method of psychometric function is used to introduce the calibration process of finding the ideal target size to solve the problem of the accuracy in drawing movement by reducing the errors in the motor noise of rapid drawing movement.

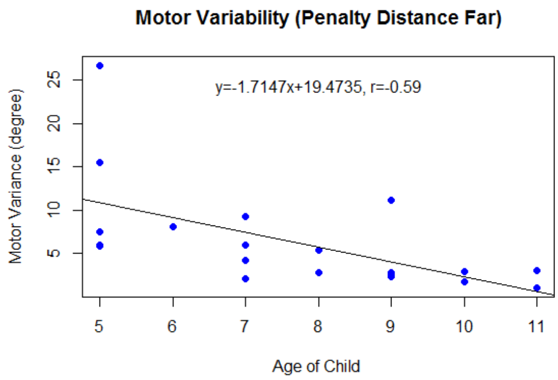
The overall child users performance was correlated with the optimal rate as predicted by the model suggesting that children were making near optimal adaptation. Apart from that, there was an improvement on the number of child users that followed the prediction shift of the model. Another main research question was also answered in this study. The result from the analysis shows that adaptation to motor variability explain age-



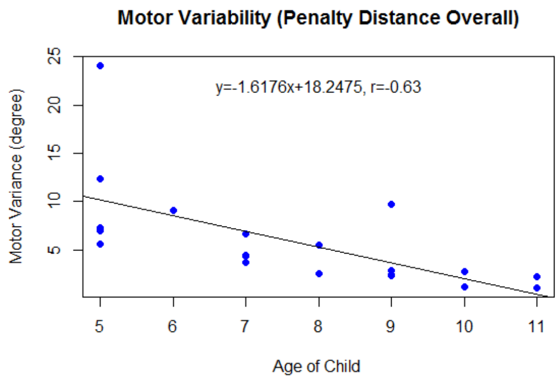
a: Drawing variance for penalty condition 1.



b: Drawing variance for penalty condition 2.



c: Drawing variance for penalty condition 3.



d: Drawing variance for all penalty conditions.

Figure 5.9: Age related to motor variance.

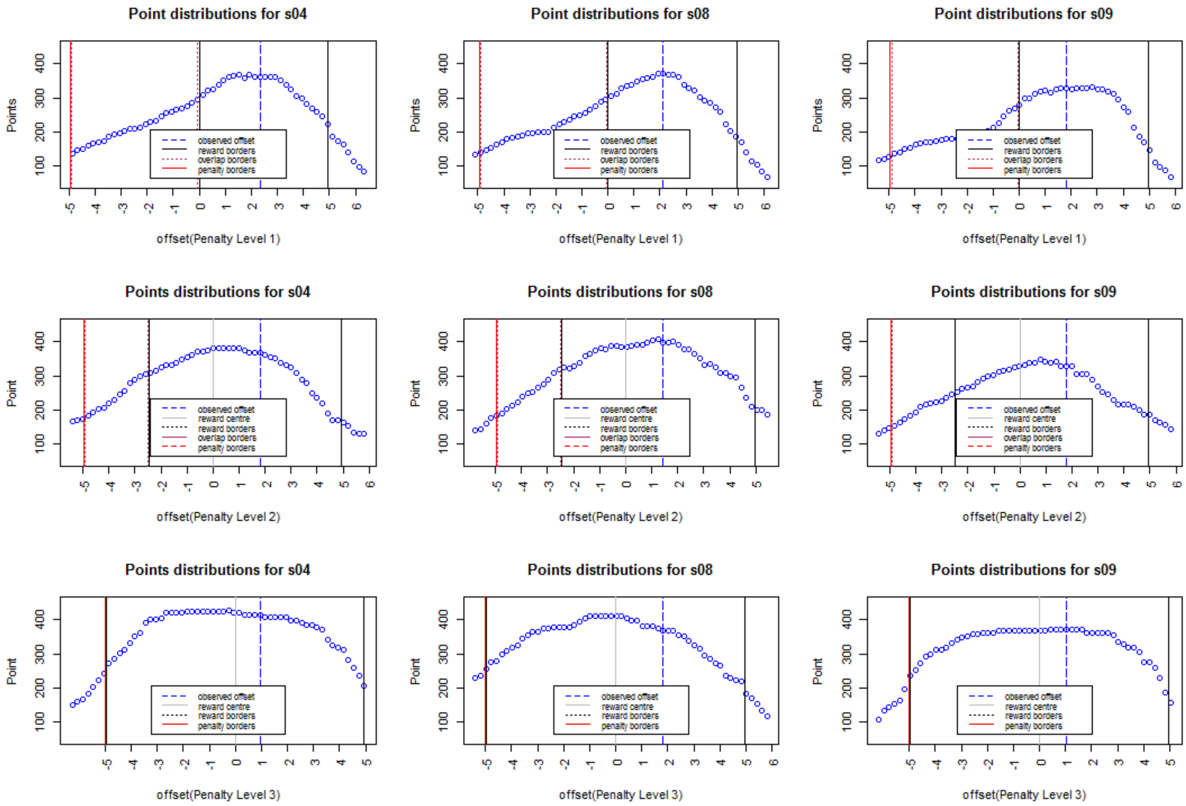


Figure 5.10: A direct comparison of observed aim points with the experimental data for subject s04, s08 and s09. The data points from these subjects were using the same target size one. The columns represent the subjects and the rows represent the penalty conditions with penalty distance 1 as *close*, penalty distance 2 as *medium* and penalty distance 3 as *far*.

related changes in the drawing performance of the current study. There was an account of larger motor variability among younger child users and smaller motor variability visible among older child users. This is interesting as motor variability explains age psychological development changes, adaptation occurs to all child users. This has been proven true for all penalty conditions in this study. The current study successfully overcome the problems in the ecology of drawing task in the drawing software addressed in the second study. Apart from that, the result of this study also argues that children below 8 years old could not integrate visual and haptic information optimally (Gori et al., 2008). This study has shown that child users below the age of 8 in this study were showing near optimal adaptation to drawing strategies. This shows that given a task with a reward of utility function, children below 8 years old can adapt to touch and visual cue in an optimal manner. Given the current study has shown evidence that children below 8 years old were showing near optimal adaptation to the drawing strategies on a touch screen, this chapter contributes to the work of the thesis that while variability is a function of development whilst adaptation is not. Adaptation occurs according to their own motor variability. The approach taken has clearly strengthened the ecology task of the study, thus presented a stronger conclusion from the result of the study.

5.6 Limitation

This study use simple drawing lines that might have been lacking functional meaning of pictorial form for children. The task may not be as appealing or engaging to the natural task of join the dots as conducted in the previous studies. In the current experimental work, few child users requested to complete the task after half way through before completing all the tasks. In contrast to the second study, although the task was more difficult, child users were seen enjoying and eager to complete all the drawing tasks. Some of them even requested to perform the drawing tasks again after completion. That was not the case in the current study. Children lacking of motivation to completing the tasks until the end of session showed that there are other limitations in the current study that need to be addressed. If there was a reward feedback given at the end of each drawing task, what was missing then? Definitely, the utility function of the drawing task need to be strengthened to overcome the motivational context issue among children's drawing behaviour in the current study.

Of other limitations, the current study did not used circles but a semi circular shape as the target and penalty regions. This could give a more convenient effect for a child to aim at the target. In addition, the point for background or outside region was higher than the penalty point even for the previous study. In Trommershäuser et al. (2003b) work, the penalty point is set lower than the background. This discrepancy may effect the result of the study. Therefore, a replication of the study is inevitable to firmly conclude the result of the study. A replication of this study would probably be close to the design of Trommershäuser et al. (2003b) work and at the same time can preserve the interest of children to get them engaged in drawing as they did in the earlier studies. These are the fundamental keys that need to be addressed and strengthened in the design as a closure for the empirical work.

CHAPTER 6

STUDY 4: DRAWING AND STROKE ATTRIBUTES

6.1 Introduction

This chapter describes the fourth study (Study 4) of the experimental work on childrens drawing on a tablet. The goals of Study 4 were threefold:- (1) to replicate the results of Study 2 and 3; (2) to strengthen the utility component of the framework into the design of the drawing tasks; and (3) to explore stroke attributes among children drawing lines.

The results from Study 2 and 3 showed that children adapt their drawing strategies to their own motor variability and to the limitations of tablets and drawing softwares. Although both results showed that adaptations were near optimal, there were rooms for improvement in the design of the tasks specifically on the components of the framework. The studies needed to be replicated in order to achieve a firm and strong final conclusion of the work. This requires strengthening the three theoretical components framework into the design of the drawing software. Study 2 had a limitation in the ecology component of the tasks, which affected the mechanism of childrens capability to perform well in the task. The limitation issue was addressed in Study 3 where ecology component of the task was modified. However, another problem surfaced in Study 3; the utility function was not firmly established into the design of the drawing task. As a result, children showed less interest to complete the whole tasks. This is where the importance of Study 4 lies; to address issues from previous studies and introduce improvements on the drawing tasks. In particular, the issue of the utility function was addressed and strengthened. Observation on child participants from Study 1 and 2 showed the participants were more engaged and willing to spend more time on the drawing tasks compared to participants from Study 3. Therefore, *join-the-dots* was used once again in the current study (Study

4) to sustain children interest, but with some improvement on the reward and drawing feedbacks included. Following Janssen & Gray (2012), I identified when, what and how to reward articulately according to the design of the tasks. This is explained in detail in the Method section of 6.3.2. The current study concluded the experiment and firmly answered the main research questions, that are: (1) "How do children adapt their drawing strategies according to their own motor variability and to the limitations of tablet and drawing application?"; (2) "How do a child adapt to the drawing actions according to his/her own motor variability?"; and (3) "Does adaptation to motor variability explain age-related changes in drawing performance?". Therefore, Study 4 is now ready to explore other attributes that covers the basic element of stroke making.

In the previous experimental work of this thesis, all drawing tasks were related to performing simple straight lines. The aim of these work were to find out how children adapt their drawing actions to drawing on a tablet. As such, drawing actions were revolved around drawing simple lines of users strokes. A closer and more focused work is necessary to explore and understand what are the attributions of these lines when children draw on a touch screen. Van Sommers (1984); Sommers (1989) provided an interesting cognitive framework for understanding the act of drawing. He extended the list of graphic production rules in terms of placement, progression and ordering. The placement refers to the starting location for a drawn segment (e.g., at the top of paper); the progression refers to the choice of movement direction (e.g., left to right); and the ordering refers to the elementary movements forming the drawing sequence (e.g., anchoring the next segment drawn to the previous drawing segment). According to Thomassen & Tibosch (1991), the execution of a geometrical pattern drawing appears to be governed by a set of graphical rules that are biased to reduced costs in movement planning. The bias to draw in a certain way could reflect subject's adaptation to drawing action and movement on paper. While this graphical production rules appeared in children's drawing on paper, it is interesting to know whether geometrical patterns also appeared in children's drawing on a touch screen. This can be investigated under the ecology task of the current drawing software which used the convention of a simple drawing line. In the next section, I will explain about the graphical rules and routines mentioned in the literature and how it can be explored and studied under the same theoretical framework of the current drawing task.

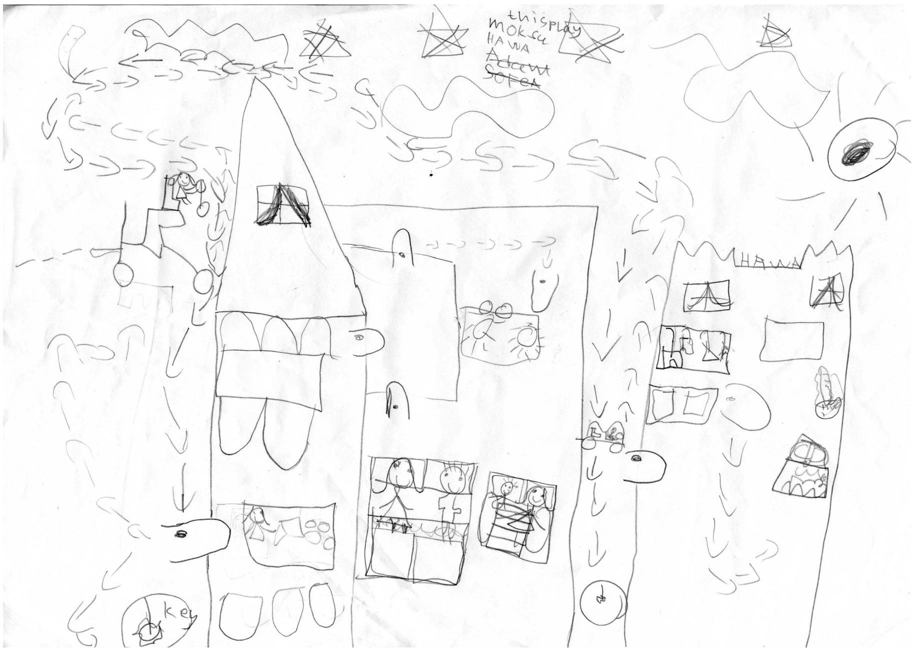


Figure 6.1: How I spend my weekend (5 years old)

6.2 Stroke attributes

Literature studies on stroke making generally touch on the aspect of graphic rules or graphic routines; which described a set of principles or rules that specify elements such as where to start and how to proceed in children's drawing. The preferences of starting from the upper left hand corner of the page (starting rule), drawing from top to bottom and left to right (progression rule) over other directions are among the salient drawing strategy that could exhibit the influential of reading and writing (Pemberton, 1987; Lange-Küttner, 1998). They are based on two factors; (1) the position and movement of arm and fingers (Meulenbroek & Thomassen, 1991); which lead to (2) development of rules of sequence and direction (Goodnow & Levine, 1973; Pemberton, 1987). As such, how we choose to draw a particular shape following a certain sequence depends on where we positioned our arm and fingers when drawing. For example, to draw a horizontal line, the motor control for positioning the arm and fingers are more demanding than drawing a vertical line; the latter requires the hand and fingers to move congruently while the former requires it to move incongruently (Van Sommers, 1984; Meulenbroek & Thomassen, 1991). This could be the reason why stroke making in horizontal direction has larger variability than in other direction among children's drawing (e.g., Serpell, 1971; Meulenbroek & Thomassen, 1991). This shows that the positions of arm, hand and fingers can influence the accuracy of stroke making. Thus, this has shed a light for Study 4 to investigate on stroke making in terms of its accuracy in drawing performance on a touch screen.

According to N. H. Freeman (1980), based on type of drawing shapes and position of arm and fingers; both factors could influence the preferences of drawing position and orientation. Looking closely at early studies of Gesell & Ames (1946), children's drawing strategies seem to depend on the type of shape they draw. For example, to draw a cross, children basically start by drawing a vertical line in downward direction before moving to draw a horizontal line from left to right. When it comes to a diamond shape, children tend to draw four lines in downward direction that show great variance to the actual pattern. Their work has shown that children developmental drawing strategies changed according to the order, direction and orientation of lines drawn influenced by the type of drawing figures or the way instructions were given. This could be the reason why children participants in Study 1 were making drawing errors in the direction of drawing lines. The overall dots that formed a hint of the drawing shape influenced children's drawing action on how drawing should be progressed. Therefore, to reduce drawing errors or action leading to biases in Study 4, the task was built with the absence of visual drawing figures of any reference. Children can only know what they draw after completing repeated trials of drawn line segments. This is to ensure that the accuracy of stroke making can be identified without any biases and a comparison between different stroke making attributes can be performed. In an attempt to study the accuracy of stroke attributes, the fourth research question is then derived; "What are the accuracy among stroke attributes when drawing on a touch screen?".

Stroke attributes in this study follow the literature work of stroke making when drawing on paper. According to Gesell & Ames (1946), drawings are basically individually analyzed according to attributes such as placement, direction, continuity, length and the order of strokes. In study 4, the drawing attributes are compiled according to (1) *type*, (2) *direction* and (3) *length* of strokes. The *type* of strokes can be categorized as *horizontal, vertical* and *diagonal*, where work from the literature has stated that (1) *horizontal* strokes show larger variability than other strokes; while (2) *diagonal* strokes show larger variability than *orthogonal* strokes (*horizontal* and *vertical*). The confusion between *horizontal-vertical* strokes were more common than *diagonal*-right and *diagonal*-left strokes (Berman, 1976). This *type* of stroke making is also related to *direction* of strokes; where *left-to-right* lines are known to show larger variability than *top-to-bottom* movement. Would this mean that *horizontal* direction strokes are more variable than *vertical* direction strokes? It is also established that the *left-to-right* direction strokes are more stable than *right-to-left* direction strokes and *top-to-bottom* direction strokes are more stable than *bottom-to-top* direction strokes (Goodnow & Levine, 1973; Pemberton, 1987). Pemberton (1987) believes that the preference direction of strokes are due to a rule-governed thought perceptual process. For *diagonal* or *oblique* directions, Meulenbroek & Thomassen (1991) shows that the change of arm position would affect the directional preferences of *oblique* directions more than *orthogonal* directions. All other directions show larger variability than *horizontal* and *vertical* directions. Their work also shows that, it is easier to draw *diagonal* lines to the *top-right* hand corner and to the *bottom-left* hand corner using hand movements but for finger movements, this would be the opposite, where it is easier to draw *diagonal* lines to the *top-left* hand corner and to the *bottom-right* hand corner. Berman (1976) stated that oblique lines are seen to be less accurate due to the reference of the square border of drawing material. The *length* of strokes on the other hand, followed Gepshtein et al. (2007) analysis of adult's ballistic aim point based on distance. Their work found that longer strokes would yield to more motor errors, resulting in higher variability for the aim point than to shorter strokes. While most of stroke making are studied under the literature of drawing on paper, Study 4 investigates these drawing attributes not only on surface interaction but also in according to the manipulation of input methods (pen/finger). The accuracy of stroke making can be affected on the way they draw, either using a single stroke or a hand grip control.

For this study, less or high variability in stroke-making is assumed to be related to small or larger shift from the centre of non-overlapping reward region. Instead of investigating the variability of stroke-making according to subject's own motor variance, this study looks into the amount of shifts depending on the penalty distance of *close*, *medium* and *far* from one drawing attributes to the other. I predicted that *aim point* that shows less or more shift from the penalty region in one stroke category (e.g., horizontal) over the other (e.g., vertical), yields to better accuracy. This is motivated by Gepshtein et al. (2007) work where when aiming point started from the centre of the screen towards different distance of the target regions in different directions; the targets that were near show less shift on the *aimpoints* than the targets that were further away. Below are the predicted list of drawing attributes defined earlier, which built to the hypothesis of stroke attributes:-

i type *Horizontal* strokes make larger shift than *vertical* strokes.

ii type *Diagonal* strokes make larger shift than *orthogonal* strokes.

iii direction *Right-to-left* directions make larger shift than *left-to-right*.

iv direction *Bottom-to-top* directions make larger shift than *top-to-bottom*.

v direction *Left-to-right* directions make larger shift than *top-to-bottom*.

vi length *Large* strokes make larger shift than *shorter* strokes.

These hypotheses motivated the following up questions such as:- (1) Which strokes make larger shift over one another? *Diagonal*-left or *diagonal*-right?; and (2) Do *top-left to bottom-right* direction lines make larger shift than *top-right to bottom-left* and *bottom-left to top-right* directions make larger shift than *bottom-right to top-left*? The experimental work of this study mainly investigates whether children are adaptive to the penalty structure of the drawing task and also identifies which stroke making shows more accuracy when drawing on a touch screen surfaces.

6.3 Method

6.3.1 Apparatus

Refer to section 3.4.1.

6.3.2 Stimulus

a: A fish. b: Crocodiles. c: Grasses.
d: A tree. e: A crown. f: A star-leaf.
g: A dragon. h: A spring. i: Drying clothes.

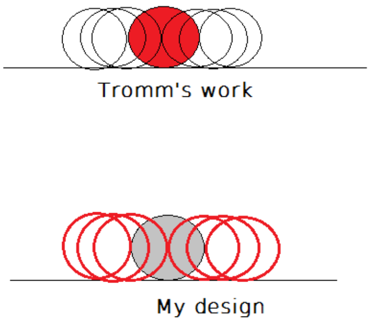
Figure 6.2: Common drawing figures used in the experimental drawing tasks.

The task is generally similar to *Join the Dots* task of previous studies; Study 1 and 2. In this study, all black dots were paired with a red dot in circle shapes; all with one standard size. There was no black target that was not paired with a red dot in this design. The size was chosen based on the analysis and experiences from the previous studies. It was tested during a pilot study, to ensure the convenience for younger children participants. The placement of the penalty regions on the other hand, remained the same as in Study 2 as shown in Figure 4.2.

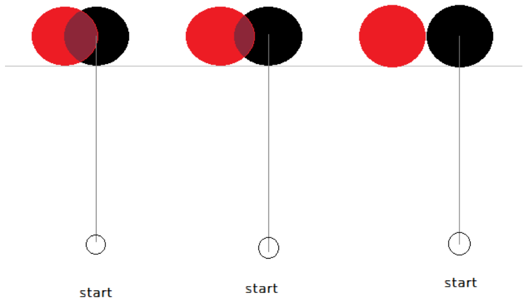
There were 14 new drawing figures used in the drawing tasks comprised of common objects such as fish, tree, crown, dragon (refer to Figure 6.2 for complete list of the objects). Also, one drawing figure of a spaceship was modified from Study 2; was included as one of the drawing tasks. Each of these 15 drawing figures were used twice, making it a total of 30 drawing tasks altogether and they were sorted in random order. In this study, when the same drawing figure was displayed for the second time, the directions of the strokes were changed to the opposite direction. For example, when the same drawing figure appeared for a second time, the child participants would need to connect the dots in an order opposite to that drawing first appeared. This means that the last dot for the drawing figure shall now become the first dot and the last dot would become the first or the starting dot. The end result of all drawing lines would form a drawing picture, comprised of lines from different directions and angles. The directions of drawing lines were categorized according to type of strokes. A stroke here refers to subject's strokes that formed a line based from an initial position towards a target.

There were three types of strokes; *vertical*, *horizontal* and *diagonal*. *Vertical* strokes comprised of *top-to-bottom* and *bottom-to-top* directions; *horizontal* strokes comprised of *left-to-right* and *right-to-left* directions and *diagonal* strokes comprised of *left-bottom to right-top*, *right-top to left-bottom*, *right-bottom to left-top* and *left-top to right-bottom* directions. Each type of stroke has three type of lengths; *short*, *medium* and *long*. The lengths and directions were carefully designed based on the type of strokes used in previous studies. The length of the strokes should not be neither too short nor too long. The length should not be either too easy or too hard to perform by children participants. Refer Figure 6.4 for examples of strokes. All data of the strokes were recorded in the analysis according to their types and attributes (e.g., length and direction) and also based on the penalty distance (e.g., *close*, *medium* and *far*).

Figure 6.3 shows how reward and penalty regions were placed according to different distances in the drawing task, perpendicular to the starting point of the drawing line. Penalty regions were placed in contrast to Trommershäuser et al. (2003b) work as shown in the Figure 6.3a. Their target regions were displaced in different distances from the penalty region, while in my study, the penalty regions were displaced in different distances from the reward region conveniently for touch action. The penalty regions were placed either to the left or right side of reward regions throughout the tasks.



a: Comparison of penalty regions placement to Trommershäuser et al. (2003b).



b: Drawing line from an initial point towards a target region with different displacement of penalty region.

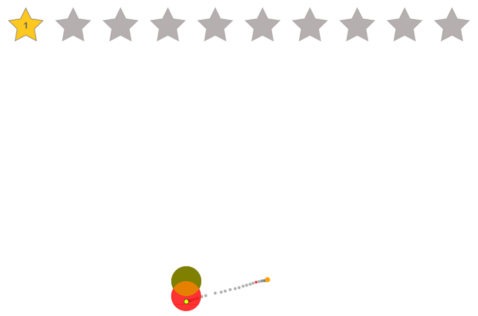
Figure 6.3: Stimulus configuration similar to Study 2. The black area (non-overlapping reward region) gives 10 stars, the red area (non-overlapping penalty region) gives 1 star, the maroon area (overlapping reward and penalty region) gives 3 stars and background area (outside) gives 4 star.

The *end point* of each stroke was defined as the point where the subjects lifted their fingers or pen each time they reached the target area. This approach was closer to Trommershäuser et al. (2003b) work compared to the previous studies that did not take the final end point but instead took the point that hit the boundary of the target area. In this study, subjects were required to lift their finger or pen when they reached the target regions in order to get the scoring points. The scoring point rules were; 10 stars given for an end point in the non-overlapping reward region, 3 stars in the overlapping reward region, 1 star in the non-overlapping penalty region and 4 stars for outside of the region or background area. Unlike Study 2 and 3, Study 4 added a point for background score. This is more similar to Trommershäuser et al. (2003b) design where the background point was put higher than the overlapping region. Therefore, the optimal point is expected to be closer to the background (and away from the penalty area) than in Study 2 and 3. The display affect of the reward is also included here. If subject scored 10 stars, the line shown would be a solid line; if they scored 3 stars, half of the line would shown in a dotted line, while 1 star and 4 stars, the whole line would be shown as a dotted lines. This was to give differentiation effect to the strokes when their end points landed in different regions specified before. Example of effects to the drawing lines are shown in Figure 6.4.

There was only one starting point and target area (comprised of reward and penalty regions) appeared at one time during interaction. All other targets were made invisible to the subjects. This was following closely the design used in Study 3. All the drawing lines made by the subjects were displayed at the same time when the drawing task was finished. This means that the subjects shall be able to view the complete image of their

a: A medium diagonal line that hit the overlapped regions.

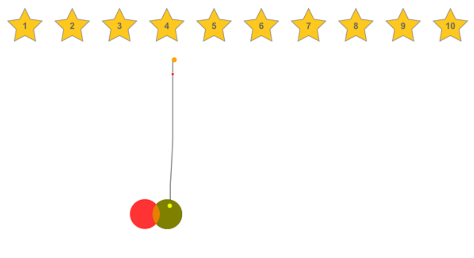
b: A medium diagonal line that hit the outside region.



c: A short diagonal line that hit the non-overlapping penalty region.

d: A long diagonal line that hit the non-overlapping reward region.

e: A long horizontal line that hit the overlapped regions.

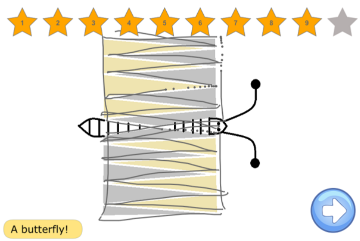


f: A long vertical line that hit the non-overlapping reward region.

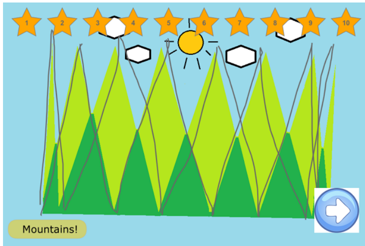
Figure 6.4: Attribute of line strokes that hit the penalty and reward regions with scored points.

drawings at the end of each tasks.

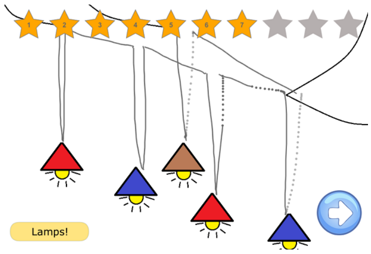
6.3.3 Procedure



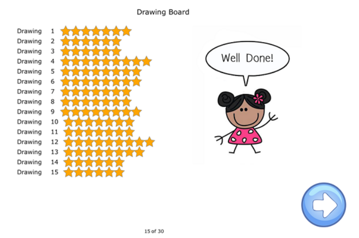
a: A full drawn picture in the drawing task, a butterfly.



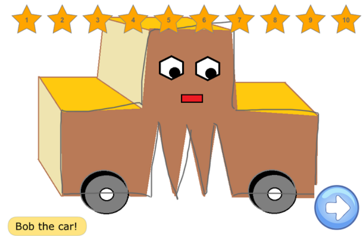
b: A full drawn picture in the drawing task, mountains.



c: A full drawn picture in the drawing task, lamps.



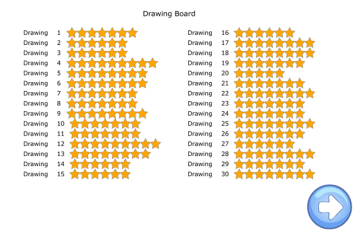
d: Drawing scores for 15 drawing tasks.



e: A full drawn picture in the drawing task, Bob the car.

f: A full drawn picture in the drawing task, buildings.

g: Drawing scores for 21 drawing tasks shown after 3 drawing tasks completed.



h: Drawing scores for 30 completed drawing tasks.

i: Total number of stars achieved.

Figure 6.5: The overall steps of the drawing tasks in the main experimental session.

The experiment started with 10 to 15 minutes of practice session. In the practice session, children participants would need to draw lines towards reward regions within a time limit of 850ms. This time was set as the time constraint for drawing a single line towards a target. After few trials, subjects would need to draw a line towards a target that comprised of reward and penalty regions within the same time set. Once they were familiar with the task and understood the scoring points system, they were allowed to take a break for about 5 to 10 minutes before the main session started.

In the main session, children participants would need to draw a line from a starting point towards a target of reward and penalty regions. Once the drawing line reached the target, scored points would be shown on top of the page. 10 stars would be rewarded for a full score and the lowest score would be just one star. Children participants would need to make repetitive drawing lines in different directions and angles. A full drawn picture would appear at the end, formed by all the lines drawn by the children. The final and complete picture of the drawing figure drawn would also show the final score in the form of yellow and numbered stars on top of the page. Each drawing scores for one drawing set of one drawing figure will be accumulated at the end of all the tasks. The lines of the complete drawing figure would have either solid, half solid and half dotted or completely dotted lines depending on the accuracy of the children drawings. This effect would help children to better understand the scoring system. The score point of each drawing would be updated on a score board after every three drawing sets. Children could rest or take a break when the score board page was displayed before moving on to the next task. These steps would continue until all 30 drawing tasks were completed. On average, the experiments lasted between 40 minutes to 1 hour per child participant. Figure 6.5 pictures the steps needed to be taken for the main session.

6.3.4 Experimental Design

The experiment was within participants design for independent variables: penalty region (*close*, *medium* and *far*) and between participants design for drawing medium (*finger* or *pen*). There were two experimental groups; one group (n = 33) drawing with *finger* and the other group (n = 32) drew using *pen*. All participants from both groups went through the same drawing tasks. It was a one data point per participant, a three-by-two analysis of a mixed between-within subjects analysis of variance; of whether subject's drawing action was affected by using the drawing medium inputs and whether it was affected by the penalty conditions. Figure 4.4 in Study 2 shows a similar design layout of the experiment.

6.3.5 Subjects

There were 70 children participants (35 boys and 35 girls) with age ranging from 5 to 12 years old. 5 children participants were discarded from the experiment (4 boys and 1 girl); 2 of them were left-handed and the other 3 were not able to follow the order of the task. Therefore, only 65 participants' data were used for analysis with a mean age of 7.83 years (*SD*=2.17 years). There was a mixed background (nationalities/races) of children that were recruited through contact with their parents and a school. The experiment was conducted either through home visits, at Water Mill Close School, meetings at agreed convenient locations (e.g., cafe) and at University of Birmingham. Some of the subjects attended primary schools in Birmingham, UK and some were home schooled. These children participants on average had 1 hour and 40 minutes of tablets and touchscreen exposures in a day. Figure 6.6 shows the age distribution of children participants.

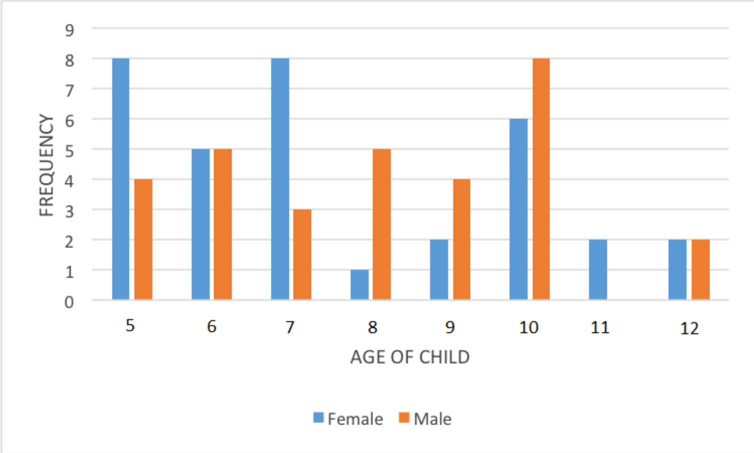


Figure 6.6: Age distribution for children participants in study 4.

6.3.6 Instruction

All parents and children participants had given their informed consent to participate in the experiment. Subjects were informed about the number of stars for reward and penalty conditions. All were unaware of the hypotheses under tests. Subjects did a practice session prior to the main session. Subjects were required to complete all the drawing tasks in the main session. If they were unable to complete all the drawing tasks, their data would have to be discarded from the analysis. At the end of the sessions, subjects received a small gift as token of appreciation for their participation.

6.3.7 Pilot Study

Pilot study was conducted involving six children participants prior to the main experiment. These children participated in the previous experimental work of Study 3. They were between age of 6 to 10. The purpose of the experiment was to make sure that children participants did not face any problem during interaction and that the data extracted from users strokes and scores given were accurate and as per the scoring system. No changes were required post to the pilot study, which indicated that the drawing software was ready for experimental work.

6.3.8 Data Analysis

There were n=168 *endpoints* for penalty region *close*; n=168 *endpoints* for penalty region *medium*; and n=164 *endpoints* for penalty region *far.* These *endpoints* can be categorized according to the types and directions of line strokes. There were n=168 *small* strokes; n=164 *medium* strokes; and n=180 *large* strokes; where there were n=158 *horizontal* strokes; n=152 *vertical* strokes; and n=204 *diagonal* strokes, with n=100 *diagonal-to-the-right* strokes and n=104 *diagonal-to-the-left* strokes. Standard fixed angles were used to determine the type of line strokes they belong to. Any line that looks between a *diagonal* and a *horizontal* or a *vertical* line, would need to have the angle checked to make sure it falls under the right type of line strokes. For example, to determine between either both types of line strokes, if the line was less than 25 degree, it falls under *horizontal* or *vertical* type, else it would fall under *diagonal* type. All line strokes were checked and categorized accordingly in the code prior to experimental run. This was to ensure the accuracy of the result later on.

The calculation of *end point* and predictions for optimal *aim point*, performance and efficiency should be referred to section 4.3.8. The *endpoints* from the drawing data were recorded according to penalty region distances for strokes type, length and direction. The average drawing time and number of stars achieved were also recorded for each participant.

6.4 Result

There were n=65 data participants. A mixed between-within subjects analysis of variance was conducted to assess the impact of two different medium of drawing inputs (*finger* and *pen stylus*) on participants *endpoint* strokes according to penalty distances (*close*, *medium* and *far*). There was a substantial main effect for penalty distances, *Wilks' Lambda* = 0.05, $F(2,62)=575.224$, $p<0.0001$, *partial eta squared* = 0.949, with both groups of different drawing medium showing an increase distance of endpoints when the penalty distance are closer to the target area (see Figure 6.7). However, there was no significant main effect and interaction between drawing with finger and drawing using pen stylus, suggesting no difference in the effectiveness when drawing using these two mediums. The rest of the results in the experiment are explained according to the research questions stated.

	Drawing with Finger			Drawing using Pen		
Penalty Distance	*n*	*M*	*SD*	*n*	*M*	*SD*
Close	33	9.5264285	3.06718418	32	8.9540381	2.85873194
Medium	33	4.6515251	2.53013370	32	3.9905285	2.52333125
Far	33	.5612265	2.45137060	32	.1728405	2.78995665

Figure 6.7: The mean and standard deviation for Study 4 data participants

(1) "How do children adapt their drawing strategies according to their own motor variability and to the limitations of tablet and drawing application?"

Figure 6.8 shows the observed and optimal aim points for all subjects in the three penalty conditions. To know whether subjects observed aim points were almost optimal or not, the graph shows that there was a strong positive significant correlation between optimal offsets and observed offsets for all subjects in all penalty conditions with; $p<0.0001$ for *close* distance, r = 0.971; *medium* distance, r = 0.998; and *far* distance, r = 0.999 with n=65 and $p<0.0001$. The result suggested that subjects aiming point were close to the optimal aim points. The diagonal line in the figure shows y=x. Most of the aim points in the graph are above the diagonal line due to the distance of observed aim points larger than the distance of optimal aim points respective to the penalty regions. The efficiency of the overall subjects performance was 98.07

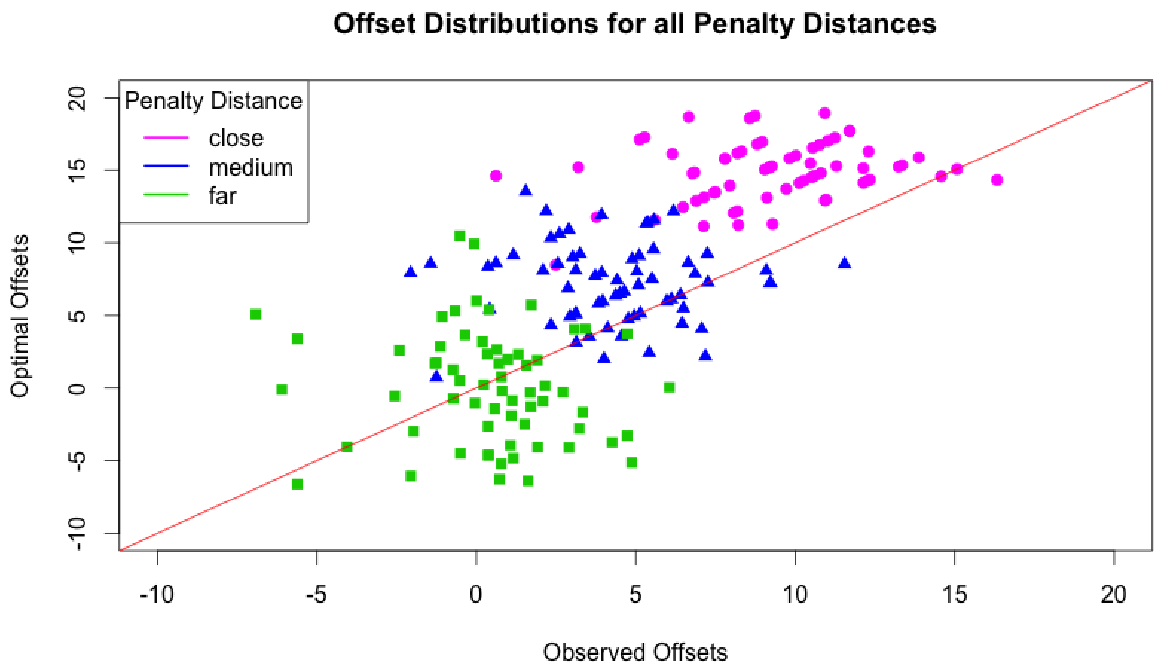


Figure 6.9: The observed and optimal offsets of all penalty distances for all subjects.

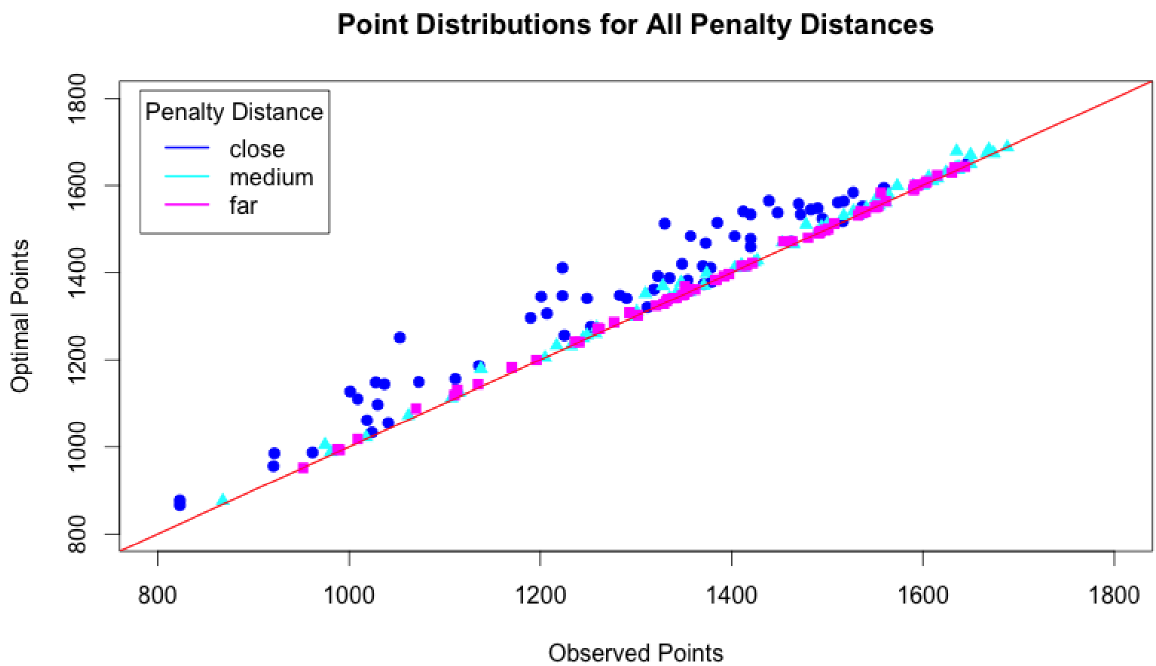


Figure 6.8: The observed and optimal points of all penalty distances for all subjects.

Subjects were found to alter their aiming point away from the penalty area according to the model prediction explained in section 4.2.1. The model predicted that closer penalty distance yield more shift to the aim point and further penalty distance yield less shift to the aim point. This is shown in Figure 6.9 where aim points in pink showed larger shift, aim points in blue showed moderate shift and aim points in green showed the least shift respective to the distance of penalty regions. Subjects shifted their aiming point more when the penalty region was placed closer to target region and shifted lesser when the penalty region was far from the target region. According to Figure 6.9, the graph shown a positive significant correlation between subjects' observed offsets and optimal offsets given, r=0.731, n=195 with p<0.0001. But how can we know whether subjects were truly making near-optimal adaptation? Perhaps subjects were aiming at the centre of non-overlapping reward region and they were just adapting less?

To find out whether subjects were aiming at the centre of non-overlapping reward region, rather than optimizing or whether they were truly making optimal adaptation, an additional analysis to cater subjects' aiming points relative to the centre of non-overlapping reward region was made. The optimal aim offsets versus observed aim offsets were plotted for all penalty conditions according to the centre of non-overlapping reward region as shown in Figure 6.10. From the graph shown, the scatter-plots do not resolve around the centre of non-overlapping reward region but rather shifted towards the background especially the aim points for penalty distance *close* and *medium*. The pink aim points were shifted further away from the centre but towards the background which is further away above the diagonal line. This is reasonable as the point for background or outside region was higher than the point for penalty region. The blue aim points show moderate shift away from the centre towards the background. The green aim points on the other hand did not show much effect whether they shift away from the centre as the penalty region was placed far away from the reward region and that the reward region had a full circle area by itself. Therefore, in response to the question: *Isn't that subjects were aiming what was left at the centre?*. The graph displayed in Figure 6.10 offer a better explanation.

(2) "How do a child adapt to the drawing actions according to his/her own motor variability?"

The end points from each line strokes were extracted and accumulated to an average aim point according to the penalty conditions. These aim points maximize expected utility from the gain functions as predicted by decision theory, explained in Chapter 4 of Study 2. To understand how observed and optimal aim points were obtained for each subject, an example illustration of the data are shown in Figure 6.11 and 6.12. A direct

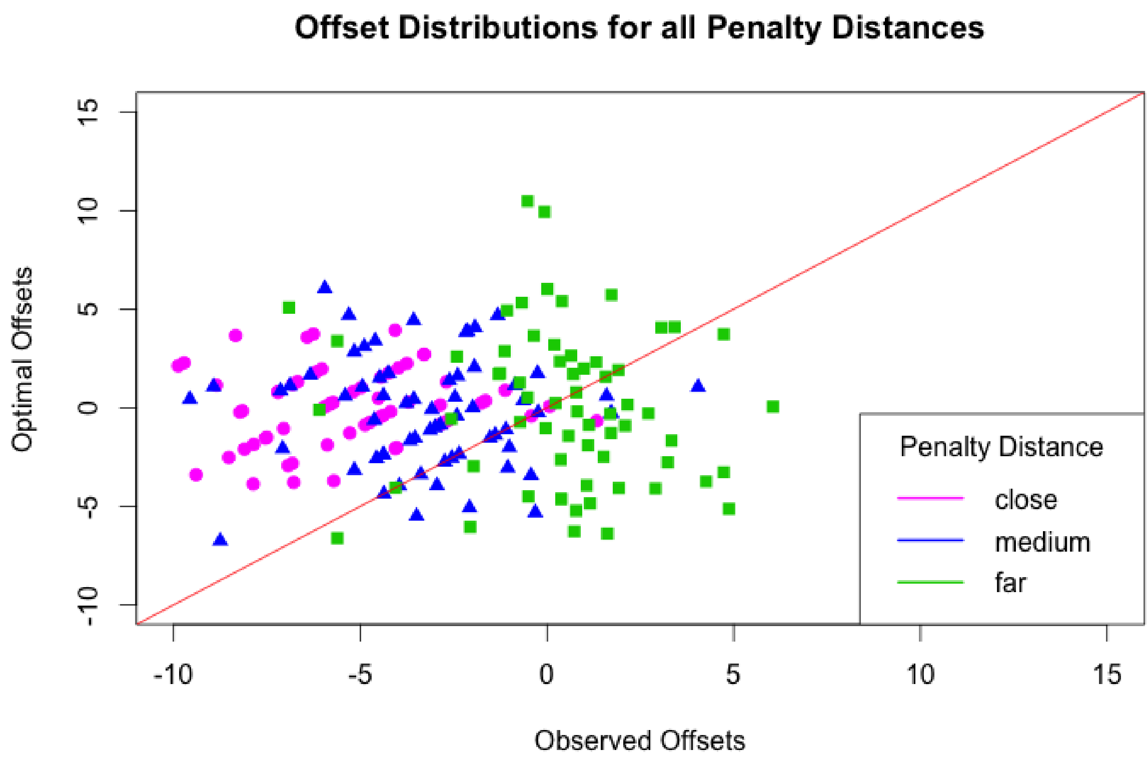


Figure 6.10: The observed and optimal offsets relative to the centre of non-overlapping reward region

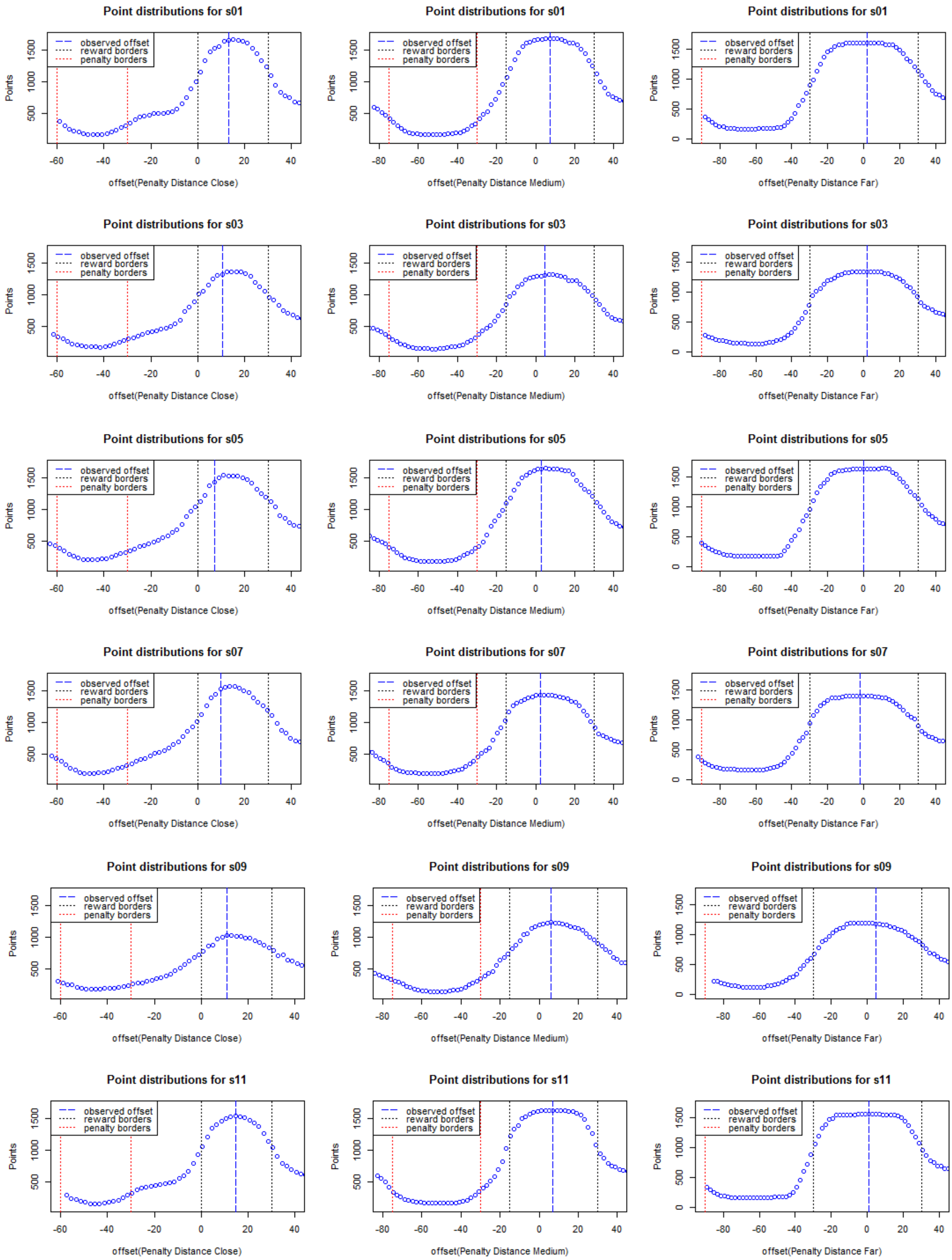


Figure 6.11: A direct comparison of observed and optimal aim points with the experimental data for the first six subjects that draw with their finger-tips. The columns represent the subjects and the rows represent the penalty conditions.

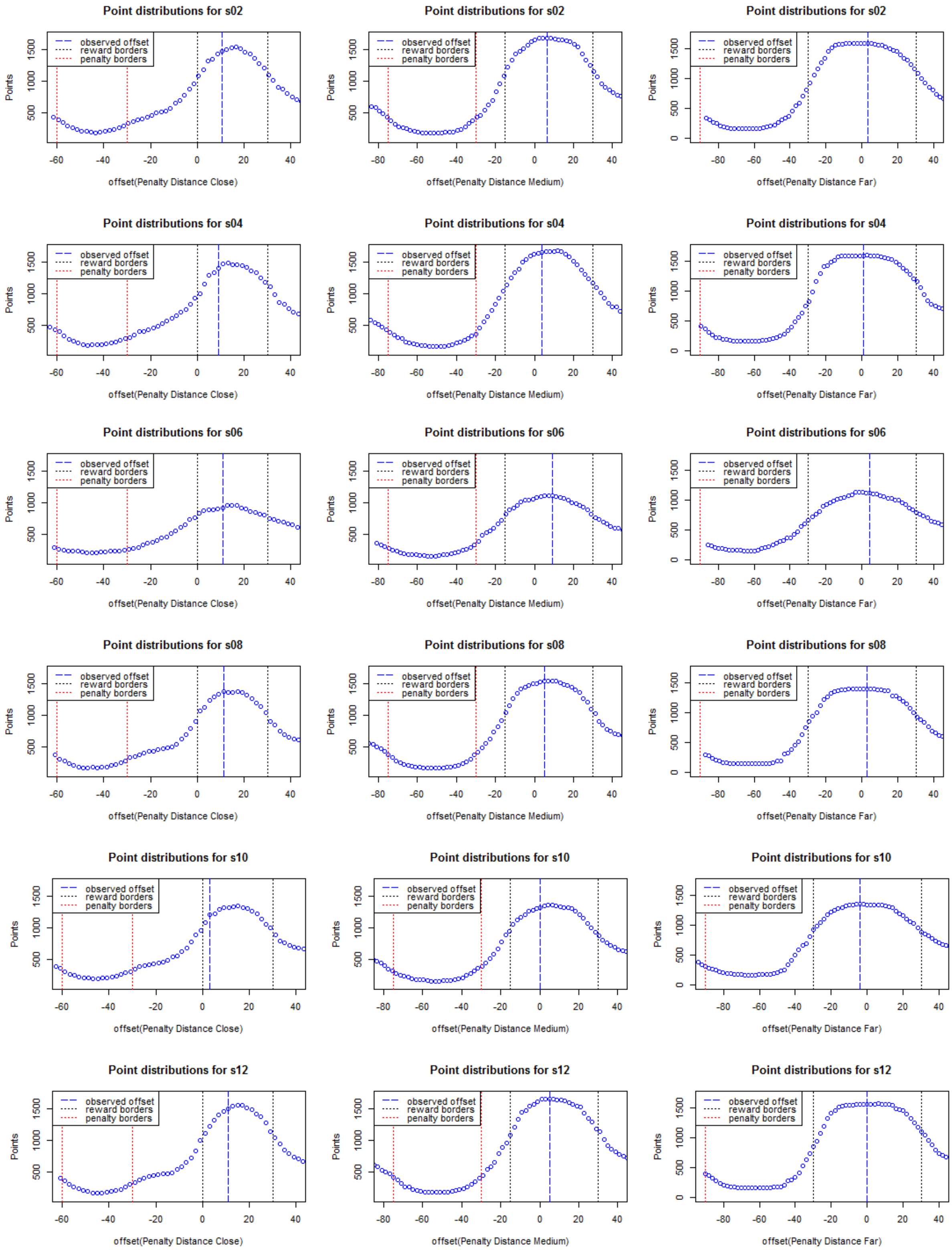


Figure 6.12: A direct comparison of observed and optimal aim points with the experimental data for the first six subjects that draw using a pen stylus. The columns represent the subjects and the rows represent the penalty conditions.

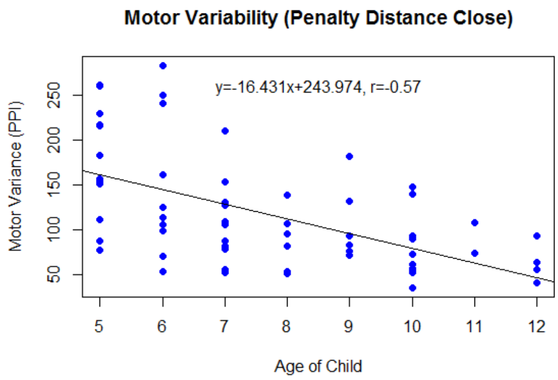
comparison of the prediction values x_{opt} was made in this figure. The drawing movement endpoints are distributed around this mean end point according to a bi-variate Gaussian distribution. The experimental data was simulated for every subject in every penalty conditions using equation 4.3 to find the aim points for every offset of margin 0.2. The colored lines marked the bars for the boundary regions of reward and penalty, yielding to overlapped and outside regions. The dashed blue lines marked subject's aim point, which is the observed aim point. Every aim point had a score point which maximized the expected gain from all of possibilities region. The highest plot point is the optimal aim point. Result earlier has shown that there was a significant correlation between observed and optimal aim point. The result suggested that both aim points are not far away from each other indication that every subject was making near optimal adaptation. This could be observed from the distance between the observed aim points with the highest aim points in each graphs as shown in both Figure 6.11 and 6.12. The rest of other children participants graphs are put in the Appendix section. The aim point distributions for this Study 4 are far smoother and cleaner than previous aim points of other studies. This show that the consistency of the curve data may exhibit the accuracy of the data more.

(3) "Does adaptation to motor variability explain age-related changes in drawing performance?"

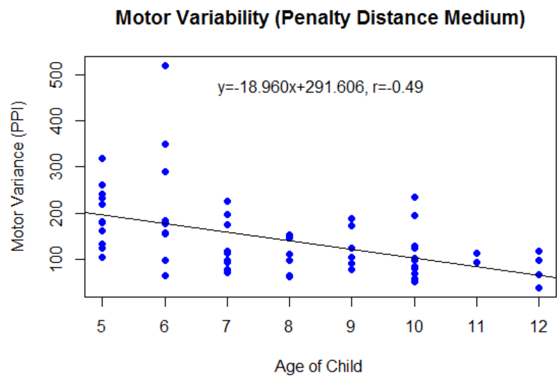
The results from this study have shown that there were strong negative significant correlations between age of children and their motor variance. Younger children showed higher motor variance than older children. According to the graphs shown in Figure 6.13, the correlation between age of child and motor variance were all p<0.0001, which for penalty distance *close*, r=-0.57; *medium*, r=-0.495; *far*, r=-0.485, and the average for all penalty distances is r=-0.534. Therefore, do adaptation to motor variability explain age-related changes in drawing performances? Figure 6.13 offers the answer.

(4) "What are the accuracy among stroke attributes when drawing on a touch screen?"

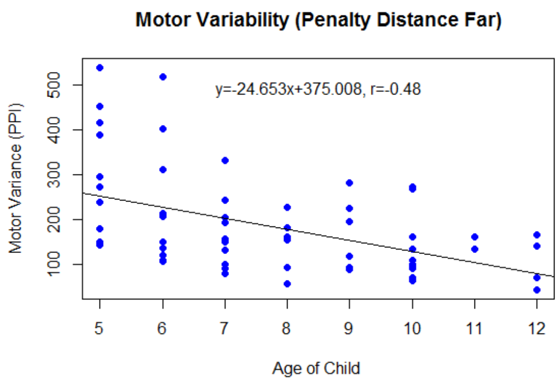
A study on stroke accuracy was conducted using a two by two analysis of mixed between-within subjects analysis of variance. The dependent variables taken are two stroke attributes of between design and the independent variables are two mode of input (finger/pen) of within design. The result suggested that for type of strokes, there is no statistically difference when comparing between*horizontal* and *vertical* strokes. However, when comparing between *diagonal* and *orthogonal* strokes, there is a statistical significant difference in the main effects given, r=0.84, n=65 with p=0.001; with no interaction



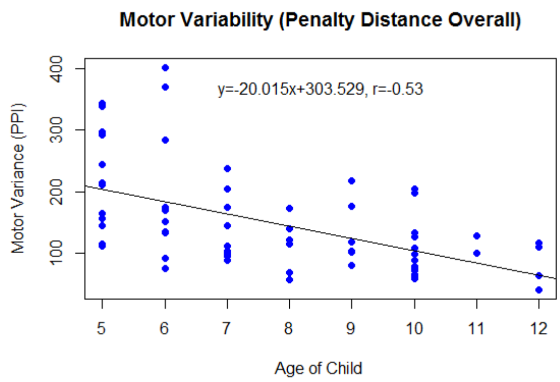
a: Drawing variance for penalty distance *close*.



b: Drawing variance for penalty distance *medium*.



c: Drawing variance for penalty distance *far*.



d: Drawing variance for all penalty conditions.

Figure 6.13: Age related changes to motor variance.

effect on the mode of input. The *diagonal* strokes give a higher average than the *orthogonal* strokes. Given that there is an effect on the *diagonal* strokes, a comparison was made between *diagonal-left* and *diagonal-right* strokes but no statistical different was found. For direction of strokes, there are no statistically difference when comparing between*bottom-to-top* with *top-to-bottom* strokes and *left-to-right* with *top-to-bottom* strokes. A statistical significant difference occurred in the main effect only of *left-to-right* and *right-to-left* strokes, with *left-to-right* showing higher average given, r=0.908, n=65 with p=0.014; with no interaction effect on the mode of input. No statistical difference reported in any of the strokes comparison for *length* of strokes.

6.5 Discussion

This Study 4 aimed to investigate how every child user responds to the reward and penalty effects of the drawing task in a one to one intervention that formed a drawing picture at the end of every drawing set. The utility function for this study has been strengthened where improvements were made on the reward and drawing feedback. In the reward function, the scoring points were set according to a ten point stars and followed closely how Trommershäuser et al. (2003a) rewarded the points according to different regions. While in terms of drawing feedback, when a child user gained a certain score or numbers of golden stars, an effect occurred to user drawing strokes according to the scores. For example, a score of ten stars produce a solid line but any scores below ten, the strokes would produce either a half dotted or fully dotted lines instead. These effects helped child users to quickly realize how well are they doing in the tasks. This also helped to understand how the completed drawing figure was rewarded. Basically if the final drawing figure was drawn mostly by solid lines, the score should be high and if the final drawing figure is shown mostly in dotted lines, the score rewarded was expected to be low. Therefore, each final drawing figure could be considered as the drawing feedback. These reward and drawing feedback are also important for child user to appreciate the utility function in a drawing task. After all, most importantly, the goal should be to convey a reward representation that is recognizable to children and capture their interest when drawing. By improving the utility function of the task, all the three theoretical components (*utility, ecology* and *mechanism*) are now strengthened. Therefore, Study 4 has given a concrete evidence that children adapt near optimal to their own drawing strategies according to their own motor variability, to the motivational context of action and to the limitation of tablet and drawing software. The result from this study has also shown that while variability is a function of development, adaptation is not. Adaptation is sensitive to changes in the motor variability of the individual.

For stroke making, a study has been done to find the accuracy among stroke attributes presented earlier. Since the drawing task involves making simple straight lines, the study examines attributes relating to *types*, *directions* and *lengths* of strokes involved. Again, in Study 4, the manipulation of finger and pen as the input method for drawing has been added. Since the design of the drawing in the current study is different than the previous studies, an effect on the input method might occur. Although there is no significant difference in the input method of the reward and penalty effects and stroke attributes, it was worth examined to ensure if any discrepancy occurs given a modification in the design of the study. According to the study made for stroke making, *diagonal* type of stroke showing higher variability than *orthogonal* strokes as predicted, making the latter more accurately performed by children participant. For direction strokes, *left-to-right* strokes shows higher variability than *right-to-left* strokes making the latter more accurately performed which contradict with the assumption made. According to the literature, *right-to-left* strokes showed larger shifts than the *left-to-right* strokes when drawing on paper. The contradiction might be probably due to the affordance of material used when drawing. Drawing on a touch screen could yield different effects to the graphical rules depicted. Drawing lines from *right-to-left* on a paper for example, would require a subject to exert or use some pressure when drawing; thus giving different experience than drawing using the tip of a finger on a glass touch surface. Other attributes did not reported any significant result.

6.6 Summary

This chapter is a closure for all the empirical work conducted as explained in previous chapters. Through phases and stages of modification and replication towards the drawing software, the drawing task used in the empirical work for Study 4 was established by strengthening the three theoretical components of the framework. Ensuring the strength and quality of the components; *utility*, *ecology* and *mechanism* are vital to have a better understanding on children's drawing behaviour when interaction with technology is involved. Therefore, the experimental work in this Study 4 has given a convincing and solid result to the work of this thesis.

CHAPTER 7

GENERAL DISCUSSION

In summary, my work reviewed the theoretical and empirical aspects of children's drawing, under the theoretical framework of Adaptive Interaction. The framework helped to gain a better understanding of psychological processes involved in drawing and drawing development in order to investigate children's drawing using technology. The goal of this framework was to provide a predictive, cumulative, and explanatory account of adaptation of children's drawing strategies on a tablet. To achieve that, the framework (Figure 2.1) studied children's drawing through a utility maximization approach that derives its explanatory power from three components of human behaviour, which are *ecology*, *utility* and information processing *mechanisms*, as explained in detail in the Chapter of Background and Theoretical Framework of section 2. These three components were used, revised and strengthened throughout the four experimental studies as explained in Chapter 3 to 6 of this thesis in shaping an established design of a drawing task to children. With a solid design of a drawing task built on these three components, the fourth component of the framework, the *strategy space* was used as the empirical approach to solve the work of the thesis. Therefore, this chapter discusses and summarizes the work of the thesis according to the empirical and theoretical perspectives.

Before embarking to summarize all the studies, consideration should be given whether there are any threats to the validity of the results. Participants from Study 1 were not recruited for Study 2 as there are similarities in the design of the task. There were repeating participants from Study 1 and 2 in Study 3 as the design in Study 3 was different than the previous studies. However, no previous participants were repeating in the experiment of Study 4, where all children participant are new to the experiment. Prior to every data collection, a pilot test was conducted to making sure that children participant understand well the task given and the overall operation was conducted smoothly. The design, functionality and overall interaction during experiment had been taken care of and improved well prior to the main studies. During main experiments, the experimenter had brief parents well enough and inform that the child/children participant should not be interfered by the parents, carers or other children if any when performing the task. A convenient spot or place for a child to draw was requested where other possibilities of interruption can be avoided such as noise from the television or other people conversation. The setting of the experiments were conducted in a way close to making sure that children are doing a natural task that they normally do when drawing. This includes an ice breaking session of the children with the experimenter and informing them that they could take a break in between or to stop at anytime they wish. This was to ensure that children participation were voluntarily act basis. Such interruptions occurred during the experiment were observed and if potentially causing any effect towards the study, had been considerately taken off from the data analysis. To avoid any threat of validity, during experimentation itself, a few rules had been outlined to making sure all procedures of the experiment are carried well and standardized across all participants. Random allocation to groups had been done to making sure in avoiding any confounding factor. These necessary steps were taken to ensure that there are no threats to the validity of the result for all experimental studies.

7.1 Empirical perspective

At the beginning of my thesis, I set out to answer three research questions from the empirical approach. The empirical and modeling work in Chapter 3 to 6 had helped to provide answers to these questions. These answers are summarized below.

(1) "How do children adapt their drawing strategies according to their own motor variability and to the limitations of tablet and drawing application?"

The aim of the first question is to seek whether children adapt to their own motor variability and to the limitations of tablet and drawing application. In order to answer this question, Chapter 3 of Study 1 firstly examined whether children's behaviour can adapt to the drawing conditions set on the drawing software. The aim of Study 1 was to understand the effects on children's drawing strategies to the reward conditions introduced. These reward conditions were manipulated to examine how children's drawing behaviour differs under two different reward functions with *Low* reward gives easy access to ten stars and *High* reward makes it more difficult to attain higher number of stars. The result suggested that children were more motivated to draw better when the number of stars or reward were harder to obtain rather than when it was easier to do so. Study 1 provided encouraging evidence that children do adapt their drawing actions to the reward functions. However, do children adapt optimally? Therefore, Chapter 4 of Study 2 is designed to answer this question. The approach used in Study 2 followed Trommershäuser, Maloney, & Landy (2003b) work where the model of movement planning in section 4.2.1 was used to examine whether children were responsive to the penalty and reward structures of the task. The model predicts that when a penalty region is placed closeby to the reward region, subject would make a larger shift of the aim point and that they would make lesser shift of the aim point when the penalty region is placed further. The result of Study 2 was only 4% less from optimal performance. Although children were following the prediction of the model, many drawing data were discarded due to biases occurred in the children's drawing movement. The limitation of Study 2 implies that a next study was required to test this prediction again. Therefore, Chapter 5 of Study 3 followed the same hypothesis and experimental conditions of Study 2. The design of the task in Study 3 was modified to a one to one intervention to overcome the limitation in Study 2. Again, the result was showing good prediction to the model, this time with 7% efficiency but the only limitation was children were getting less interested to perform the drawing task. Chapter 6 of Study 4 was replicated to improve the design of the task so that it would be more engaging to children. Here, the external reward function and the drawing task design itself was modified and improved to fit the purpose. Study 4 successfully overcome all limitations occurred in the previous studies. Children gained interest and no biases were found in the drawing data. Study 4 suggested that children showed near optimal adaptation not only to their drawing strategies, but also according to their own motor variability and to the limitations imposed by the drawing environment set in the software. The efficiency of childen's performance was 2% higher than Study 2 and 3.

In summary, the limitations imposed by the question are perceived as uncertainty in the movement plan which may cost error when making drawing actions. The uncertainty covers the sensory environment such as constraints on tablets and drawing tool and stochastic information represented in the motor and cognitive tasks. In an attempt to strategies the drawing actions, the motor system needs to plan and control complex motor coordination to make the best possible decision in making movement. These probabilities (reward and losses) and costs (motor commands) in the motor task can be framed under Bayesian Decision Theory to quantify trade-off between various decision in estimating the expected value of its actions. Figure 6.9 shows that children adapted by adjusting their drawing actions according to the model of movement plan of Bayesian Decision Theory. Thus, they make near optimal adaptation as illustrated in Figure 6.8, where their performance deviated only about 2 percent from optimal performance. The result suggested that, subjects take into account their intrinsic motor variability and therefore, surprisingly select efficient strategies that come close to maximizing the expected gain (reward and losses) in the motor system. It is possible that a child's strategy for drawing on a tablet can be understood as a Bayesian adaptation to movement variability, motivation and limitations of the device surface.

(2) "How do a child adapt to the drawing actions according to his/her own motor variability?"

The aim of this question is to investigate every child user's drawing performance. This was studied by comparing users aim points to the optimal aim points. The aim point chosen by a user is a consequence of that particular individual's bivariate Gaussian distribution of end points around each possible aim point and the objective function. The aim point predicted by decision theory is the aim point that maximizes expected utility, and there is no need to fit the parameters of the decision model to the outcome data. Figure 4.11 and 4.12 in Chapter 4 of Study 2 show the the aim point distributions of six children participants. The first three graphs referred to subjects drawing with finger and the following three graphs referred to subjects drawing using a pen. The aim point distributions in these graphs are showing left-skewed, which mean subject's aim points are at the left side of the peak. The peaks in the graphs indicate the optimal aim points predicted by the objective function. For Study 3 of Chapter 5, the graphs of aim point distributions are shown in Figure 5.10 with three graphs referring to subject's drawing using finger. The aim point distributions for the first subject are slightly left-skewed while the third subject aim points are showing normal distribution. In Study 4 of Chapter 6, the graph distributions of Figure 6.11(drawing using finger) and 6.12(drawing with a pen) are showing normal distributions especially on penalty region *far*. The aim point distributions in Study 4 are showing a nice curve of Gaussian distributions compared to Study 2 and 3. These aim point distributions show that children were adapting according to their own motor variability.

In summary, children participant maximize their expected utility from all possibilities of reward and losses in the drawing task. Their aim point from the drawing tracings are distributed around the mean end point of bi-variate Gaussian distribution. The study shows that a child adapt to their own motor variability in a goal-directed drawing task.

(3) "Does adaptation to motor variability explain age-related changes in drawing performance?"

The aim of this question is to find out whether younger children show higher motor variance than older children. Study 2 of Chapter 4 did not show any relationship between the age of a child and motor variance. This was due to the limitation of Study 2 that had affected how children plan their drawing. Study 3 of Chapter 5 has shown a strong significant correlations between the two, as shown in Figure 5.9. The correlation looks as though there was a curvilinear relationship between age and variance. This was perhaps inevitable given that variance cannot be reduced below zero; but perhaps, it is worth fitting a power function? Study 4 of Chapter 6 is also showing a strong significant correlations between age of child and their motor variance. Figure 6.13 in Study 4 shows that younger children showed higher motor variance than older children in the drawing performance. It is known that younger children have less developed perceptual and motor coordination in drawing than older children. Due to their higher motor variance, younger children may draw less accurately than older children. This can be observed from Study 1 that shows older child users draw faster and scored higher than younger child users shown in Figure 3.7a and 3.7b. This suggested that, as children grow, their drawing strategies improved. This explains that while variability is a function of development, adaptation is not. Adaptation is sensitive to changes in the motor variability of the individual.

7.2 Theoretical perspective

The answers from the empirical perspective has helped to answer two further questions. These questions are mentioned earlier in the thesis and are raised by the theoretical framework of Adaptive Interaction. These answers are summarized below.

(1) "How would children draw on a tablet given that they have cognitive and motor limitations?"

This question influences the technical approach that I took in the studies, and it revolves around the "process oriented" approach of children's drawing that focuses on the motor aspect of *how* children plan their drawing movement. This is concerning the cognitive *mechanism* of children from different age, in terms of their developing capability to draw on a tablet. To answer this question, the *strategy space* was used. The approach from the *strategy space* was derived, in part, from the cognitive psychology of human movement control that consisted of an empirical investigation of the extent to which a decision theoretic framework can account for drawing skills. As decision theory can be applied to conditions of both certainty or uncertainty and risk, the idea was used to understand how children adapt strategies to the risks and perceived costs of drawing errors, slips and mistakes. Therefore, a Bayesian and Statistical Decision Theory was used.

The Statistical Decision Theory has proven that, adult's performance in their aiming point is optimal under the Bayesian approach (Trommershäuser et al., 2003a, 2005, 2006; Gepshtein et al., 2007; Dean et al., 2007; Maloney & Zhang, 2010). This however, has not been tested on children hence, has motivated the work of this thesis, where; (1) the established pointing tasks, comprised of hand movement of perceptual motor skill was studied and was embedded in the context of childen's drawing; and (2) the drawing task following the established pointing tasks were examined under Bayesian approach, in order to find out whether children adapt optimally similar to adults. How could the concept pointing tasks be studied and incorporated in the context of children's drawing? A closer work to Trommershäuser et al. (2003b) was followed. This was the reason why all experimental studies in the empirical work were influenced by their work. The next paragraphs explain how the drawing tasks were designed to help investigate children's drawing movement.

Study 2 in Chapter 4 touched on drawing in the context of movement planning of Bayesian approach. The experimental hypotheses of the drawing tasks in this study, were motivated by a decision theoretic perspective on planning for drawing in which costs of interaction are balanced against the gain implicit in a rewarding drawing. In the early phase of Trommershäuser et al. (2003b) pointing task, there was a black circle placed in random locations, where adults had to aim and hit within a time limit. This black circle was considered as a target of reward region. Then, a red circle emerged next to the black circle. This was the penalty region that adults needed to avoid. Drawing task in Study 2 was designed similar to this. Instead of pointing to a target, children needed to draw a line from one point towards a target point by making a continuous contact on the screen. How would children plan their drawing strategies to achieve a high score by aiming towards a black dot and trying to avoid the red dot at the same time? Although children were showing near-optimal adaptation, there were limitations in Study 2. A large amount of data were discarded from the analysis due to some biases exhibit. When examining the findings, children were found to be making biases movement in their drawing. They tend to deviate their drawing lines to the direction of the next target areas rather than focusing to the current target. This problem was due to the drawing tasks of Study 2 mimicking the conventional way of *join-the-dots* task, where several black and red circles were placed as target and penalty areas in one drawing task page. This caused problem to how children plan their drawing strategies. Almost half of children participants in this study were not following the predictions of the model, even though the result was good. Apart from that, due to many targets in one design task, the size of the target had to be small in sizes. This was rather difficult for children to aim especially in a rapid movement task. Due to the weaknesses occured in the *ecology* of the drawing task, the limitations of Study 2 also had affected the *mechanism* of how children plan their drawing. Therefore, Study 3 had to be designed in a way that these issues were eliminated.

Study 3 in Chapter 5 had been improved in terms of the *ecology* of the tasks, where only one target at one time was placed in a single drawing task. *Join-the-dots* task had to be explicitly removed to avoid any biases in the drawing movement. In addition, a calibration process of adaptive method was introduced prior to the main task in order to get the right target size suiting every child participants. Other than that, the shape of the target was changed so that it would be easier to extract an accurate end point of users' stroke for analysis purpose. In overall, the purpose of Study 3 was to improve the cognitive *mechanism* of children from different age background ensuring them to be able to perform the tasks well. Extra attention was given in designing the *ecology* of the task to support children *mechanism* in terms of their interaction aspects of vision and touch on touch screen surface (Jansen-Osmann et al., 2002; Contreras-Vidal et al., 2005; Burge et al., 2008). This is why the Psychometric function was required in the calibration process of finding the right target size for children (Gepshtein et al., 2005). The determination to increase the accuracy of children's interaction is reflected from the modification of the task. The changes made had given improved and good result. There was only one weakness in Study 3 where children were showing lack of engagement in completing the task. Some of the children lost interest and requested to stop half way through. Given that the task was just drawing simple lines repeatedly, this was actually expected to happen. Although the components of *ecology* and *mechanism* were improved, the *utility* component in the design of the task was slightly compromised. Imposing an external reward function alone such as the work of Trommershäuser et al. (2003b) seems not adequate to strengthened the *utility* component of the task. This shows that the design of the drawing task need to establish on its *utility* component concerning the reward system that can influence children's goal-directed drawing performance. As of what accounts to a good *utility* function to children's drawing task, this is answered in the next question of the thesis:-

(2) "Why would children draw on a tablet given that there are limitations to tablet and tablet software?"

This question is concerning the "product oriented" approach of children's drawing that focuses on the cognitive aspect of *what* and *why* children draw as explained in Chapter 1 of Introduction. The *what* addressed the *ecology* of the task that gives a reasoning to *why* children would draw. The limitations mentioned in the question are related to the statistical property concerning the motor control. This means that the *ecology* of the task need to be designed in a way that is effective to children's performance and at the same time motivating enough for children to be interested in completing the task well. A good *utility* component is required. One way is to embed an external reward function in the children drawing tasks.

Study 1 in Chapter 3 was the first experimental study of the empirical work for this thesis. As mentioned, one of the main purpose of this thesis is to design a drawing task that can motivate children in terms of their action plans when drawing. This is the main factor of strengthening a *utility* component as addressed in Study 1. To do so, an external reward function was introduced by using a set of ten golden stars to rate children's drawing performance. The aim of Study 1 was to find out whether children would modify their drawing behaviour according to the reward conditions. To make the task interesting to children, *join-the-dots* task was introduced in Study 1. Following Mohd Shukri & Howes (2014), the idea was to see how children adapt to the reward conditions when tracing trajectories through the dots on touch screen surfaces using the tip of children's finger or a pen. The experiment provided encouraging evidence that children do adjust their drawing actions to the reward conditions. Its' results seem to be pointing to that children adapted to the reward functions introduced. In light of the evidence that showed children were adaptive, the sequel of the experimental studies that follows, Study 2 and 3 were conducted to investigate whether children were not only adaptive but were also optimally adaptive. This part has been explained in the first question previously. Study 3 has addressed its weaknesses in strength of the *utility* component. From there, a new study was required. This new study, Study 4 was built to revised the *utility* component of the task.

Study 4 in Chapter 6 is a replication of all previous studies conducted. The purpose of Study 4 however, was more focused on the *utility* component of the task. How can Study 4 improved the work of Study 3 when the result were already good? To look back, *utility* component under the theoretical framework of Adaptive Interaction concerns on what a person wants to do, i.e., in what they find value. Having to say that, an external reward function is not enough to the powerful contribution of a *utility* component. According to Martocchio & Webster (1992), a good instruction is more effective than a feedback or reward of the task. Drawing feedback can only be built on something, in which it should happen second. They also mentioned that feedback is of little use when there is no initial learning or surface information. This went back to what was missing in Study 3; children did not find value in the tasks that they performed. Children also sometimes feel that they are not learning anything new. rather, they were just following what was asked from them to accomplish. This was the issue I stated earlier in the Introduction of Chapter 1. Drawing literatures under the *process oriented* approach neglected the utility function in the task. It seems that the designed task of Trommershäuser et al. (2003b) work did not work well for children. An accumulated scores would probably be sufficient to motivate adult in performing a ballistic pointing task in which they might find value in doing such task. Albeit the reward of obtaining golden stars exists, children may not find repeatedly drawing simple lines of much value to their intrinsic motivation. Children intrinsic interest may have been lessen as the task continued and repeated although being externally rewarded. What was truley missing was the nature of the drawing task itself.

In Chapter 2 of Background and Theoretical Framework, I have described about the common objects that children like to draw in the *ecology* section of 2.3. I have also explain in the *utility* section of 2.2 about the reason why children like to draw. Among them was drawing can be regarded as an act of playing. To gain children interest in drawing, these two aspects questions need to be looked at again. The element of drawing common objects need to be in the task and the concept of drawing as a play activity need to be embedded. This goes back to the design of Study 1. *Join-the-dots* task seem to be fit for children's drawing task suiting to Bayesian framework. Chapter 1 also explains in detail what account to the *utility* component of a task. However, the design needed to be modified to ensure so as it does not create any problem to the *mechanism* of how children plan to draw. Both *join-the-dot* task and the external reward function need to be carefully re-designed again. This has been addressed and explained well in Chapter 6 of Study 4.

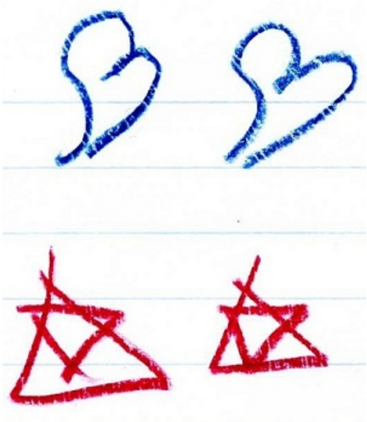
7.3 Conclusion

Looking back to the hypotheses and questions posed at the beginning of this chapter, it is now possible to conclude that Study 4 has firmly answered all the three main research questions and has given a robust conclusion to the work. Study 4 of Chapter 6 made a closure to all the empirical work by reinforcing the *utility* component into the design of children's drawing task apart from the other two components (*ecology* and *mechanism*). It is in this *utility* component that I wanted to highlight. The *utility* component embedded in the drawing task had an influence to the motivational context of action to children when drawing. The design of the task was successful and had overcome all challenges as mentioned in the earlier thesis, and limitations coming from the previous studies. Children in Study 4 were seen engaging in performing the drawing task and they were showing keen interest during the experimental sessions. Some of the children were requesting to do the drawing task again.

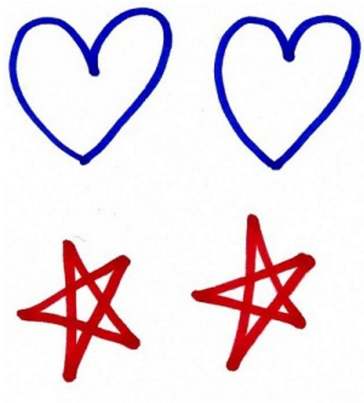
The findings from Study 4 investigation complement those of earlier studies. With a solid design of a drawing task following the Adaptive Interaction framework, Study 4 managed to explore the attributes of strokes making used in drawing. The work has provide a supplementary evidence on stroke attributes of children's drawing on a touch screen device. It introduced the basic and fundamental stroke making of drawing on a touch screen to the literature of children's drawing. The work reported in the thesis shows that a child's strategies for drawing on a tablet can be understood as a Bayesian adaptation to movement variability, motivation and the limitations of the device surface. This perspective may offer a promising mean of understanding children's drawing strategies.

7.4 Future Works

The usage of Bayesian theoretical framing of this work opens up a number of future research opportunities in understanding children's drawing. One possible area is to extend the work in the area of stroke making preferences. Study 4 covers only the basic graphical rules in strokes making. There are more interesting elements to investigate such as the placement of a starting position of a drawing and the order of a stroke. For example in a placement rule, there is a preference to start at the left and top most of the page when drawing on paper. The tendency to start from the top could possibly be due to the positioned of the fingers that are already located near to the top of the paper. Wang et al. (2013) work found that initial touch points on a screen have the tendency to be found at the left of the target position on the horizontal axis and toward the centre of the screen on the vertical axis. It is interesting to find out that there are similarities when a person is given different material and platform used to draw on. Sommers (1989) studied that children seem to follow a set of rules when copying a geometrical figures; from where to begin drawing to which directions to proceed. This leads to the next rules that is stroke ordering. Let's say, a person that wants to draw the number seven will start with a left-right strokes, followed by drawing the next strokes downward, top-bottom. How the next order of the stroke is drawn can also be looked at, to whether it is a preferred as continuous or a broken line. This can also be extended to not only on simple lines,



a: (A child's drawing) Love hearts and stars with multiple strokes.



b: An adult's drawing) Love hearts and stars with single stroke.

Figure 7.1: A comparison of an adult's and a child's heart and star shapes.

but other basic shapes such as circles, square or apex shapes. In a circular shape, the ordering of the stroke of counterclockwise was adhered the most. The convention rules of clockwise and counterclockwise as the ordering of the strokes can be used to study these shapes. By investigating these graphic skills and preferences, how graphic units are formed, combined, transformed or substituted into and for one another can be studied even on a touch screen environment.

Other possibilities are to explore children's drawing strategies that goes beyond drawing line or curvature segments. For example, how do children plan and strategize the logical structure in forming a simple shape? If we look closely at child's heart shape drawing in Figure 7.1, it consists of two strokes, one for the left side and one for the right side of the heart, while for an adult, the shape was constructed with just a stroke. Another example is a star was drawn using two triangles in different directions using multiple strokes. In comparison to an adult's drawing in Figure 7.1b, the same shapes were drawn using a single stroke. These examples are clear comparison of how children and adults composed a logical structure of a given shape differently.

Another work closer to this that can be explored on a touch screen is the classical developmental tasks such as seriation. A study from Simner et al. (1996) has shown that given a task of copying a pattern composed of rectangles, six different graphic strategies were observed in this task. The idea was to investigate how children cope with copying tasks in terms of how they organize the order of their drawing and whether they could reproduce a correct logical structure of the figure. Simner et al. (1996) work used geometrical figures that were identical to those used by Van Sommers (1984) as shown in Figure 7.2. They identified four graphic strategies from childrens copying drawing; which are isolated rectangles, juxtaposed rectangles, isolated and juxtaposed rectangles and ac-

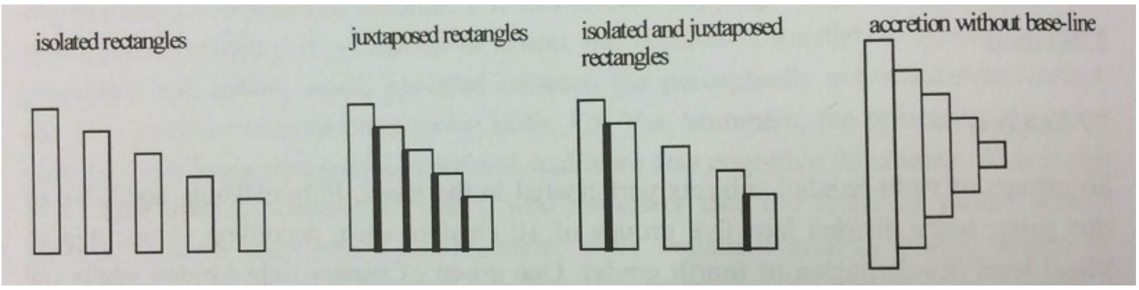


Figure 7.2: Illustration of four graphical strategies observed in Simner et al. (1996) study.

cretion without base-line (shown in Figure 7.2). They stated that the development of the graphical strategies observed from this task depends on the representational system that the child possess at that moment when recording the incoming information during copying (glance-draw-glance-draw). The copying tasks requires a translation process between what the child perceived from the drawing, followed by the action taken to draw. While the drawing strategies from these two cases were according to drawing on paper, an interesting work can be investigated for drawing on a touch screen. Also, it is also possible to develop a tool that may help children to solve the problem differently. For example, children could draw a part or a segment of a shape and just "copy and paste" it to fit into other area of the shape. Therefore, an interesting question would be how do children adapt to their drawing plan in organizing a logical structure of a graphical representations? Can these work under Bayesian approach? These concerns more on children's cognitive ability when planning their drawing.

Perhaps another possibility that could be studied is a free form drawing where the goal is to achieve the desired drawing shape or picture. There are many drawing attributes that can be examined. A few examples of decisions made when drawing an object are the variety of the object, state of objects, context of a 3d or depth environment, orientation, view point, level of detail, type of boundary and many more (Gesell & Ames, 1946; Van Sommers, 1984). The details of these attributes in drawing can be investigated with a careful plan and detail instruction to children. As grip configuration are mostly varied in free drawing (Braswell et al., 2007), free form drawing would be far more challenging to be investigated.

Future work suggested in this section can be generally grouped in two aspects of drawing performance, one associated to planning of the position of strokes or shapes in a drawing, and the other one, with the analysis of objects to be drawn. The former is related to the accuracy of contact points in a stroke while the latter relates to the correctness on the shape attributed of the drawing. The question that surfaced here is; is it possible that such tasks can be understood through the lens of Bayesian decision theory? However, the fundamental of children drawing strategies in simple drawing lines under decision theory have been provided in this thesis. With that in mind, I hope this thesis opens up more possibilities pertaining children work not only in drawing but other related tasks using the same theoretical framework to understand children's interaction with technology better, on the ground of theoretical and empirical perspective.

REFERENCES

Adams, E. (2002). 220 power drawing.

Adi-Japha, E., Levin, I., & Solomon, S. (1998). Emergence of representation in drawing: The relation between kinematic and referential aspects. *Cognitive Development*, *13*(1), 25–51.

Anning, A. (1997). Drawing out ideas: Graphicacy and young children. *International Journal of Technology and Design Education*, *7*(3), 219–239.

Anning, A. (2000). Professionals talking about young children's drawing: the impact of their beliefs on practice.

Anning, A., & Edwards, A. (2006). *Promoting children's learning from birth to five: Developing the new early years professional*. McGraw-Hill Education (UK).

Anning, A., & Ring, K. (2004). *Making sense of children's drawings*. McGraw-Hill Education (UK).

Anthony, L., Brown, Q., Nias, J., Tate, B., & Mohan, S. (2012). Interaction and recognition challenges in interpreting children's touch and gesture input on mobile devices. In *Proceedings of the 2012 acm international conference on interactive tabletops and surfaces* (pp. 225–234).

Arnheim, R. (1954). *Art and visual perception: A psychology of the creative eye*. Univ of California Press.

Berman, P. W. (1976). Young children's use of the frame of reference in construction of the horizontal, vertical, and oblique. *Child Development*, 259–263.

Berman, P. W., Cunningham, J. G., & Harkulich, J. (1974). Construction of the horizontal, vertical, and oblique by young children: Failure to find the" oblique effect". *Child Development*, 474–478.

Bertucco, M., Cesari, P., & Latash, M. (2013). Fitts law in early postural adjustments. *Neuroscience*, *231*, 61–69.

Braswell, G. S., & Callanan, M. A. (2003). Learning to draw recognizable graphic representations during mother-child interactions. *Merrill-Palmer Quarterly*, *49*(4), 471–494.

Braswell, G. S., Rosengren, K. S., & Pierroutsakos, S. L. (2007). Task constraints on preschool children's grip configurations during drawing. *Developmental psychobiology*, *49*(2), 216–225.

Brechet, C., Baldy, R., & Picard, D. (2009). How does sam feel?: Children's labelling and drawing of basic emotions. *British Journal of Developmental Psychology*, *27*(3), 587–606.

Broderick, P., & Laszlo, J. I. (1987). The drawing of squares and diamonds: A perceptual-motor task analysis. *Journal of Experimental Child Psychology*, *43*(1), 44–61.

Brooks, M. (2009). Drawing, visualisation and young childrens exploration of big ideas. *International Journal of Science Education*, *31*(3), 319–341.

Brown, Q., & Anthony, L. (2012). Toward comparing the touchscreen interaction patterns of kids and adults. In *Acm sigchi eist workshop.*

Burge, J., Ernst, M. O., & Banks, M. S. (2008). The statistical determinants of adaptation rate in human reaching. *Journal of Vision*, *8*(4), 20–20.

Burkitt, E., Jolley, R., & Rose, S. (2010). The attitudes and practices that shape children's drawing experience at home and at school. *International Journal of Art & Design Education*, *29*(3), 257–270.

Carothers, T., & Gardner, H. (1979). When children's drawings become art: The emergence of aesthetic production and perception. *Developmental Psychology*, *15*(5), 570.

Carruthers, E., & Worthington, M. (2011). *Understanding children's mathematical graphics: Beginnings in play: Beginnings in play.* McGraw-Hill Education (UK).

Chapuis, O., & Dragicevic, P. (2011). Effects of motor scale, visual scale, and quantization on small target acquisition difficulty. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *18*(3), 13.

Cherney, I. D., Seiwert, C. S., Dickey, T. M., & Flichtbeil, J. D. (2006). Childrens drawings: A mirror to their minds. *Educational Psychology*, *26*(1), 127–142.

Contreras-Vidal, J. L., Bo, J., Boudreau, J. P., & Clark, J. E. (2005). Development of visuomotor representations for hand movement in young children. *Experimental Brain Research*, *162*(2), 155–164.

Copple, C., & Gardner, H. (1981). *Artful scribbles: The significance of children's drawings.* JSTOR.

Cox, M. (1981). One thing behind another: Problems of representation in children's drawings. *Educational Psychology*, *1*(4), 275–287.

Cox, S. (2009). Intention and meaning in young children's drawing. *Readings in Primary Art Education*, 185.

Davis, A. M. (1983). Contextual sensitivity in young children's drawings. *Journal of Experimental Child Psychology*, *35*(3), 478–486.

Dayan, P., & Daw, N. D. (2008). Decision theory, reinforcement learning, and the brain. *Cognitive, Affective, & Behavioral Neuroscience*, *8*(4), 429–453.

Dean, M., Wu, S.-W., & Maloney, L. T. (2007). Trading off speed and accuracy in rapid, goal-directed movements. *Journal of Vision*, *7*(5), 10.

Donker, A., & Reitsma, P. (2007). Aiming and clicking in young childrens use of the computer mouse. *Computers in Human Behavior*, *23*(6), 2863–2874.

Einarsdottir, J., Dockett, S., & Perry, B. (2009). Making meaning: Childrens perspectives expressed through drawings. *Early child development and care*, *179*(2), 217–232.

Felixbrod, J. J., & O'Leary, K. D. (1973). Effects of reinforcement on children's academic behavior as a function of self-determined and externally imposed contingencies1. *Journal of Applied Behavior Analysis*, *6*(2), 241–250.

Festinger, L. (1954). A theory of social comparison processes. *Human relations*, *7*(2), 117–140.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology*, *47*(6), 381.

Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of experimental psychology*, *67*(2), 103.

Freeman, N., Eiser, C., & Sayers, J. (1977). Children's strategies in producing three-dimensional relationships on a two-dimensional surface. *Journal of Experimental Child Psychology*, *23*(2), 305–314.

Freeman, N. H. (1972). Process and product in children's drawing. *Perception*, *1*(2), 123–140.

Freeman, N. H. (1980). *Strategies of representation in young children: Analysis of spatial skills and drawing processes.* Academic Press London.

Gardner, H. (1980). *Artful scribbles: The significance of children's drawings.* Basic Books.

Gardner, H., & Wolf, D. (1987). The symbolic products of early childhood.

Gepshtein, S., Burge, J., Ernst, M. O., & Banks, M. S. (2005). The combination of vision and touch depends on spatial proximity. *Journal of Vision*, *5*(11), 7–7.

Gepshtein, S., Seydell, A., & Trommershäuser, J. (2007). Optimality of human movement under natural variations of visual–motor uncertainty. *Journal of Vision*, *7*(5), 13.

Gesell, A., & Ames, L. B. (1946). The development of directionality in drawing. *The Pedagogical Seminary and Journal of Genetic Psychology*, *68*(1), 45–61.

Goldstein, D. M., & Wicklund, D. A. (1973). The acquisition of the diagonal concept. *Child development*, 210–213.

Goodenough, F. L. (1926). Measurement of intelligence by drawings.

Goodnow, J. J. (1978). Visible thinking: Cognitive aspects of change in drawings. *Child Development*, 637–641.

Goodnow, J. J., & Levine, R. A. (1973). the grammar of action: Sequence and syntax in children's copying. *Cognitive psychology*, *4*(1), 82–98.

Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate visual and haptic form information. *Current Biology*, *18*(9), 694–698.

Guiard, Y. (2009). The problem of consistency in the design of fitts' law experiments: Consider either target distance and width or movement form and scale. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 1809–1818).

Hamama, L., & Ronen, T. (2009). Children's drawings as a self-report measurement. *Child & Family Social Work*, *14*(1), 90–102.

Haney, W., Russell, M., & Bebell, D. (2004). Drawing on education: Using drawings to document schooling and support change. *Harvard Educational Review*, *74*(3), 241–272.

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. *Nature*, *394*(6695), 780–784.

Harter, S., & Zigler, E. (1974). The assessment of effectance motivation in normal and retarded children. *Developmental Psychology*, *10*(2), 169.

Helbig, H. B., & Ernst, M. O. (2007). Optimal integration of shape information from vision and touch. *Experimental Brain Research*, *179*(4), 595–606.

Henderson, S. E. (1993). Motor development and minor handicap.

Hope, G. (2000). Why draw anyway? the role of drawing in the childs design tool box.

Hourcade, J. P., Bederson, B. B., Druin, A., & Guimbretière, F. (2004). Differences in pointing task performance between preschool children and adults using mice. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *11*(4), 357–386.

Hudson, T. E., Maloney, L. T., & Landy, M. S. (2008). Optimal compensation for temporal uncertainty in movement planning. *PLoS Comput Biol*, *4*(7), e1000130.

Hudson, T. E., Wolfe, U., & Maloney, L. T. (2012). Speeded reaching movements around invisible obstacles. *PLoS Comput Biol*, *8*(9), e1002676.

Ingram, N., & Butterworth, G. (1989). The young child's representation of depth in drawing: Process and product. *Journal of Experimental Child Psychology*, *47*(3), 356–369.

Ives, S. W. (1984). The development of expressivity in drawing. *British Journal of Educational Psychology*, *54*(2), 152–159.

Jansen-Osmann, P., Richter, S., Konczak, J., & Kalveram, K.-T. (2002). Force adaptation transfers to untrained workspace regions in children. *Experimental Brain Research*, *143*(2), 212–220.

Janssen, C. P., & Gray, W. D. (2012). When, what, and how much to reward in reinforcement learning-based models of cognition. *Cognitive science*, *36*(2), 333–358.

Jolley, R. P., Fenn, K., & Jones, L. (2004). The development of children's expressive drawing. *British Journal of Developmental Psychology*, *22*(4), 545–567.

Jones, T. (1991). An empirical study of children's use of computer pointing devices. *Journal of Educational Computing Research*, *7*(1), 61–76.

Karmiloff-Smith, A. (1990). Constraints on representational change: Evidence from children's drawing. *Cognition*, *34*(1), 57–83.

Karniol, R., & Ross, M. (1977). The effect of performance-relevant and performance-irrelevant rewards on children's intrinsic motivation. *Child Development*, 482–487.

Kelley, H. H., et al. (1972). *Causal schemata and the attribution process.* General Learning Press Morristown, NJ.

Kellogg, R. (1959). *What children scribble and why.* NP Publications.

Kellogg, R. (1970). *Analysing childrenart.* National Press Books, Palo Alto, CA.

King-Smith, P. E., Grigsby, S. S., Vingrys, A. J., Benes, S. C., & Supowit, A. (1994). Efficient and unbiased modifications of the quest threshold method: theory, simulations, experimental evaluation and practical implementation. *Vision research*, *34*(7), 885–912.

Knill, D. C., Kersten, D., & Yuille, A. (1996). Introduction: A bayesian formulation of visual perception. *Perception as Bayesian inference*, 1–21.

Knill, D. C., & Richards, W. (1996). *Perception as bayesian inference.* Cambridge University Press.

Koppitz, E. M. (1968). *Psychological evaluation of children's human figure drawings.* Grune & Stratton.

Körding, K. P., & Wolpert, D. M. (2004). The loss function of sensorimotor learning. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(26), 9839–9842.

Krampen, M. (1991). *Childrens drawings: Iconic coding of the environment.* Springer Science & Business Media.

Lambert, J., & Bard, C. (2005). Acquisition of visuomanual skills and improvement of information processing capacities in 6-to 10-year-old children performing a 2d pointing task. *Neuroscience Letters*, *377*(1), 1–6.

Landy, M. S., Goutcher, R., Trommershäuser, J., & Mamassian, P. (2007). Visual estimation under risk. *Journal of vision*, *7*(6), 4–4.

Landy, M. S., Maloney, L. T., Johnston, E. B., & Young, M. (1995). Measurement and modeling of depth cue combination: In defense of weak fusion. *Vision research*, *35*(3), 389–412.

Landy, M. S., Trommershäuser, J., & Daw, N. D. (2012). Dynamic estimation of task-relevant variance in movement under risk. *The Journal of Neuroscience*, *32*(37), 12702–12711.

Lange-Küttner, C. (1998). Pressure, velocity, and time in speeded drawing of basic graphic patterns by young children. *Perceptual and motor skills*, *86*(3 suppl), 1299–1310.

Lange-Küttner, C., Kerzmann, A., & Heckhausen, J. (2002). The emergence of visually realistic contour in the drawing of the human figure. *British Journal of Developmental Psychology*, *20*(3), 439–463.

Lange-Küttner, C., & Reith, E. (1995). *The transformation of figurative thought: Implications of piaget and inhelder's developmental theory for children's drawings.* Harvester Wheatsheaf.

Laszlo, J., & Bairstow, P. (1983). Kinaesthesis: Its measurement, training and relationship to motor control. *The Quarterly Journal of Experimental Psychology*, *35*(2), 411–421.

Laszlo, J. I., & Broderick, P. (1985). The perceptual-motor skill of drawing. *Visual order: The nature and development of pictorial representation*, 356–373.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical society of America*, *49*(2B), 467–477.

Light, P., & Simmons, B. (1983). The effects of a communication task upon the representation of depth relationships in young children's drawings. *Journal of Experimental Child Psychology*, *35*(1), 81–92.

Light, P. H., & Humphreys, J. (1981). Internal spatial relationships in young children's drawings. *Journal of Experimental Child Psychology*, *31*(3), 521–530.

Light, P. H., & MacIntosh, E. (1980). Depth relationships in young children's drawings. *Journal of Experimental Child Psychology*, *30*(1), 79–87.

Lin, Q., Luo, J., Wu, Z., Shen, F., & Sun, Z. (2015). Characterization of fine motor development: Dynamic analysis of childrens drawing movements. *Human movement science*, *40*, 163–175.

Lowenfeld, V. (n.d.). Brittain. wl (1975). *Creative and mental growth.*

Lukens, H. T. (1896). A study of children's drawings in the early years. *The Pedagogical Seminary*, *4*(1), 79–101.

Luquet, G.-H., & Costall, A. T. (2001). *Children's drawings (le dessin enfantin).* International Specialized Book Services.

MacDonald, D., & Gustafson, B. (2004). The role of design drawing among children engaged in a parachute building activity. *Journal of technology education*, *16*(1), 55–71.

Maitin, S., Lark-Horovitz, B., Lewis, H. P., & Luca, M. (1968). *Understanding children's art for better teaching.* JSTOR.

Maloney, L. T. (2002). *Statistical decision theory and biological vision.* na.

Maloney, L. T., & Zhang, H. (2010). Decision-theoretic models of visual perception and action. *Vision research*, *50*(23), 2362–2374.

Martocchio, J. J., & Webster, J. (1992). Effects of feedback and cognitive playfulness on performance in microcomputer software training. *Personnel Psychology*, *45*(3), 553–578.

Matthews, J. (1984). Children drawing: are young children really scribbling? *Early child development and care*, *18*(1-2), 1–39.

Matthews, J. (2003). *Drawing and painting: Children and visual representation.* Sage.

Mayles, C. (1989). *Just playing.* Buckingham: Open University Press.

McKnight, L., & Fitton, D. (2010). Touch-screen technology for children: giving the right instructions and getting the right responses. In *Proceedings of the 9th international conference on interaction design and children* (pp. 238–241).

McWhinnie, H. J. (1971). Review of recent literature on figure drawing tests as related to research problems in art education. *Review of Educational Research*, *41*(2), 131–142.

Meulenbroek, R. G., & Thomassen, A. J. (1991). Stroke-direction preferences in drawing and handwriting. *Human Movement Science*, *10*(2-3), 247–270.

Meulenbroek, R. G., & Thomassen, A. J. (1993). Exploitation of elasticity as a biomechanical property in the production of graphic stroke sequences. *Acta Psychologica*, *82*(1-3), 313–327.

Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Keith Smith, J. (1988). Optimality in human motor performance: ideal control of rapid aimed movements. *Psychological review*, *95*(3), 340.

Milbrath, C. (1998). *Patterns of artistic development in children: Comparative studies of talent*. Cambridge University Press.

Mohd Shukri, S. R., & Howes, A. (2014). How do children adapt strategies when drawing on a tablet? In *Proceedings of the extended abstracts of the 32nd annual acm conference on human factors in computing systems* (pp. 1177–1182).

Morrow, L. M., & Rand, M. K. (1991). Promoting literacy during play by designing early childhood classroom environments. *The Reading Teacher*, *44*(6), 396–402.

Nihei, Y. (1983). Developmental change in covert principles for the organization of strokes in drawing and handwriting. *Acta psychologica*, *54*(1), 221–232.

Ninio, A., & Lieblich, A. (1976). The grammar of action:" phrase structure" in children's copying. *Child Development*, 846–850.

Payne, S. J., & Howes, A. (2013). Adaptive interaction: A utility maximization approach to understanding human interaction with technology. *Synthesis Lectures on Human-Centered Informatics*, *6*(1), 1–111.

Pellizzer, G., & Zesiger, P. (2009). Hypothesis regarding the transformation of the intended direction of movement during the production of graphic trajectories: A study of drawing movements in 8-to 12-year-old children. *cortex*, *45*(3), 356–367.

Pemberton, E. (1987). The drawing rules of children: Sequence and direction. *Bulletin of the Psychonomic Society*, *25*(5), 383–386.

Picard, D., Brechet, C., & Baldy, R. (2007). Expressive strategies in drawing are related to age and topic. *Journal of Nonverbal Behavior*, *31*(4), 243–257.

Picard, D., & Gauthier, C. (2012). The development of expressive drawing abilities during childhood and into adolescence. *Child Development Research*, *2012*.

Price, M., Handley, K., Millar, J., & O'Donovan, B. (2010). Feedback: all that effort, but what is the effect? *Assessment & Evaluation in Higher Education*, *35*(3), 277–289.

Price, S., Jewitt, C., & Crescenzi, L. (2015). The role of ipads in pre-school children's mark making development. *Computers & Education*, *87*, 131–141.

Punch, S. (2002). Research with children the same or different from research with adults? *Childhood*, *9*(3), 321–341.

Richards, R., Richards, R., et al. (2003). My drawing sucks!: Childrens belief in themselves as artists. In *Nzare/aare conference* (Vol. 29).

Rueckriegel, S. M., Blankenburg, F., Burghardt, R., Ehrlich, S., Henze, G., Mergl, R., & Driever, P. H. (2008). Influence of age and movement complexity on kinematic hand movement parameters in childhood and adolescence. *International Journal of Developmental Neuroscience*, *26*(7), 655–663.

Scheidt, R. A., Conditt, M. A., Secco, E. L., & Mussa-Ivaldi, F. A. (2005). Interaction of visual and proprioceptive feedback during adaptation of human reaching movements. *Journal of Neurophysiology*, *93*(6), 3200–3213.

Selfe, L. (1983). *Normal and anomalous representational drawing ability in children.* Academic Press.

Serpell, R. (1971). Preference for specific orientation of abstract shapes among zambian children. *Journal of Cross-Cultural Psychology*, *2*(3), 225–239.

Shadmehr, R., de Xivry, J. J. O., Xu-Wilson, M., & Shih, T.-Y. (2010). Temporal discounting of reward and the cost of time in motor control. *The Journal of Neuroscience*, *30*(31), 10507–10516.

Simner, M., Leedham, C., & Thomassen, A. (1996). The drawing of complex geometrical figures by children: How graphic strategies may be related to chronological age. *Handwriting and drawing research: Basic and applied issues*, 159.

Smith, M. B. (1965). Socialization for competence. *Social Science Research Council*, *19*, 17–23.

Smits-Engelsman, B., Van Galen, G., & Duysens, J. (2002). The breakdown of fitts law in rapid, reciprocal aiming movements. *Experimental Brain Research*, *145*(2), 222–230.

Smits-Engelsman, B. C., Sugden, D., & Duysens, J. (2006). Developmental trends in speed accuracy trade-off in 6–10-year-old children performing rapid reciprocal and discrete aiming movements. *Human movement science*, *25*(1), 37–49.

Sommers, P. v. (1989). A system for drawing and drawing-related neuropsychology. *Cognitive Neuropsychology*, *6*(2), 117–164.

Stetsenko, A. (1995). The psychological function of childrens drawing. a vygotskian perspective. *Drawing and looking. Hemel Hempstead: Prentice Hall/Harvester Wheatsheaf*.

Sutton, R. S., & Barto, A. G. (1998). *Reinforcement learning: An introduction* (Vol. 1) (No. 1). MIT press Cambridge.

Tabatabaey-Mashadi, N., Sudirman, R., & Khalid, P. I. (2013). An evaluation of childrens structural drawing strategies. *Jurnal Teknologi*, *61*(2).

Tallandini, M. A., & Valentini, P. (1991). Symbolic prototypes in children's drawings of schools. *The Journal of Genetic Psychology*, *152*(2), 179–190.

Tassinari, H., Hudson, T. E., & Landy, M. S. (2006). Combining priors and noisy visual cues in a rapid pointing task. *The Journal of neuroscience*, *26*(40), 10154–10163.

Thomas, G. V., & Gray, R. (1992). Children's drawings of topics differing in emotional significance–effects on placement relative to a self-drawing: a research note. *Journal of Child Psychology and Psychiatry*, *33*(6), 1097–1104.

Thomas, G. V., & Jolley, R. P. (1998). Drawing conclusions: A re-examination of empirical and conceptual bases for psychological evaluation of children from their drawings. *British Journal of Clinical Psychology*, *37*(2), 127–139.

Thomassen, A. J., & Tibosch, H. J. (1991). A quantitative model of graphic production. In *Tutorials in motor neuroscience* (pp. 269–281). Springer.

Thompson, C., & Golomb, C. (1992). *The child's creation of a pictorial world.* JSTOR.

Todorov, E. (2004). Optimality principles in sensorimotor control. *Nature neuroscience*, *7*(9), 907–915.

Toomela, A. (2002). Drawing as a verbally mediated activity: A study of relationships between verbal, motor, and visuospatial skills and drawing in children. *International Journal of Behavioral Development*, *26*(3), 234–247.

Trommershäuser, J. (2009). Biases and optimality of sensory-motor and cognitive decisions. *Progress in brain research*, *174*, 267–278.

Trommershäuser, J., Gepshtein, S., Maloney, L. T., Landy, M. S., & Banks, M. S. (2005). Optimal compensation for changes in task-relevant movement variability. *The Journal of Neuroscience*, *25*(31), 7169–7178.

Trommershäuser, J., Landy, M. S., & Maloney, L. T. (2006). Humans rapidly estimate expected gain in movement planning. *Psychological Science*, *17*(11), 981–988.

Trommershäuser, J., Maloney, L. T., & Landy, M. S. (2003a). Statistical decision theory and the selection of rapid, goal-directed movements. *JOSA A*, *20*(7), 1419–1433.

Trommershäuser, J., Maloney, L. T., & Landy, M. S. (2003b). Statistical decision theory and trade-offs in the control of motor response. *Spatial vision*, *16*(3), 255–275.

Trommershäuser, J., Maloney, L. T., & Landy, M. S. (2008a). Decision making, movement planning and statistical decision theory. *Trends in cognitive sciences*, *12*(8), 291–297.

Trommershäuser, J., Maloney, L. T., & Landy, M. S. (2008b). The expected utility of movement. *Neuroeconomics: Decision Making and the Brain, PW Glimcher, CF Camerer, E. Fehr, and RA Poldrack, eds.(Elsevier, 2009)*, 95–111.

Tu, H., Ren, X., & Zhai, S. (2015). Differences and similarities between finger and pen stroke gestures on stationary and mobile devices. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *22*(5), 22.

Van Sommers, P. (1984). *Drawing and cognition: Descriptive and experimental studies of graphic production processes.* Cambridge University Press.

Van Sommers, P. (1995). Observational, experimental and neuropsychological studies of drawing. *Drawing and looking*, 44–61.

Vatavu, R.-D., Cramariuc, G., & Schipor, D. M. (2015). Touch interaction for children aged 3 to 6 years: Experimental findings and relationship to motor skills. *International Journal of Human-Computer Studies*, *74*, 54–76.

Veale, A. (2005). Creative methodologies in participatory research with children. *Researching childrens experience: Approaches and methods*, 253–272.

Vinter, A. (1994). Hierarchy among graphic production rules: A developmental approach. *Advances in handwriting and drawing: A multidisciplinary approach*, 275–288.

Vinter, A. (1999). How meaning modifies drawing behavior in children. *Child Development*, 33–49.

Vinter, A., & Mounoud, P. (1991). Isochrony and accuracy of drawing movements in children: Effects of age and context.

Viviani, P., & Schneider, R. (1991). A developmental study of the relationship between geometry and kinematics in drawing movements. *Journal of Experimental Psychology: Human Perception and Performance*, *17*(1), 198.

Wang, Y., Yu, C., Liu, J., & Shi, Y. (2013). Understanding performance of eyes-free, absolute position control on touchable mobile phones. In *Proceedings of the 15th international conference on human-computer interaction with mobile devices and services* (pp. 79–88).

Watson, A. B., & Pelli, D. G. (1983). Quest: A bayesian adaptive psychometric method. *Perception & psychophysics*, *33*(2), 113–120.

Weiner, M. J., & Mander, A. M. (1978). The effects of reward and perception of competency upon intrinsic motivation. *Motivation and Emotion*, *2*(1), 67–73.

Wichmann, F. A., & Hill, N. J. (2001). The psychometric function: I. fitting, sampling, and goodness of fit. *Perception & psychophysics*, *63*(8), 1293–1313.

Winston, A. S., Kenyon, B., Stewardson, J., & Lepine, T. (1995). Children's sensitivity to expression of emotion in drawings. *Visual Arts Research*, 1–14.

Wolf, D., & Perry, M. D. (1988). From endpoints to repertoires: Some new conclusions about drawing development. *Journal of aesthetic Education*, *22*(1), 17–34.

Wood, E., & Hall, E. (2011). Drawings as spaces for intellectual play. *International Journal of Early Years Education*, *19*(3-4), 267–281.

Wu, S.-W., Trommershäuser, J., Maloney, L. T., & Landy, M. S. (2006). Limits to human movement planning in tasks with asymmetric gain landscapes. *Journal of Vision*, *6*(1), 5–5.

Xu, D., Read, J. C., Sim, G., & McManus, B. (2009). Experience it, draw it, rate it: capture children's experiences with their drawings. In *Proceedings of the 8th international conference on interaction design and children* (pp. 266–270).

Zhai, S., Kristensson, P. O., Appert, C., Andersen, T. H., & Cao, X. (2012). Foundational issues in touch-screen stroke gesture design-an integrative review. *Foundations and Trends in Human-Computer Interaction*, *5*(2), 97–205.

Zhi, Z., Thomas, G. V., & Robinson, E. J. (1997). Constraints on representational change: Drawing a man with two heads. *British Journal of Developmental Psychology*, *15*(3), 275–290.

APPENDIX