Embodied Cognition and Executive Functioning: The Effect of Whole Body Interaction on Children's Planning and Inhibition

Peter Edward McKenna

Submitted for the degree of Doctor of Philosophy

Heriot-Watt University

School of Management and Languages, Psychology

April 2017

ABSTRACT

Modern user interfaces (UI) are becoming more 'embodied' as they facilitate bodily processes. Games consoles now often include body tracking hardware. Tenants of the theories of embodied cognition and executive function (EF) have stipulated that cognition is to some extent tied to the motor system, and so, that cognitive processing benefits from physical interaction. To date however, the research in this domain has focussed on adult populations. Ultimately, children are going to experience this UI revolution throughout the lifespan. So, in the following thesis I examined whether whole body interaction supported by a gaming floor mat improved children's performance on a set of EF tasks. A set of new, gamified EF tasks were developed and completed using two interfaces (a floor mat and a keyboard) at separate sessions. The results revealed children were equally competent at each EF task using either device. Another notable finding was the effect of gamification on performance. The findings are discussed in the context of developmental psychology, experiment composition, and children's interactions with technology.

ACKNOWLEDGEMENTS

DECLARATION STATEMENT

Please find attached the electronic version of my PhD thesis. I confirm that the electronic version is the same version as the soft-bound version already submitted to Student Services.

<u>Research Thesis Submission</u>

Name: Peter Edward McKenna

School/PGI: School of Life Sciences

Version: First

Degree Sought: PhD

<u>Declaration</u>

In accordance with the appropriate regulations I hereby submit my thesis and I declare that:

1)   the thesis embodies the results of my own work and has been composed by myself

2)   where appropriate, I have made acknowledgement of the work of others and have made reference to work carried out in collaboration with other persons

3)   the thesis is the correct version of the thesis for submission and is the same version as any electronic/paper versions submitted*.

4)   my thesis for the award referred to, deposited in the Heriot-Watt University Library, should be made available for loan or photocopying and be available via the Institutional Repository, subject to such conditions as the Librarian may require

5)   I understand that as a student of the University I am required to abide by the Regulations of the University and to conform to its discipline.

*   Please note that it is the responsibility of the candidate to ensure that the correct version of the thesis is submitted.

Signature of Candidate: Peter McKenna

Date: 12/04/17

TABLE OF CONTENTS

TABLES

Chapter 5

FIGURES

PUBLICATIONS

McKenna, P.E., Lemon, O., Corley, M., Boa, D. & Rajendran, G. (2014). One step at a time: Multimodal interfaces and children's executive functioning. *Paper presented at the Proceedings of the IEEE conference on development and learning and epigenetic robotics (IEEE ICDL-EPIROB 2014).*

INTRODUCTION

From the earliest days of videogame creation, with examples such as Spacewar in 1961, the games console industry has witnessed a huge growth in popularity and technological sophistication. In their earliest iterations, video games were played using keyboards, joysticks and button pads, testing the players fine motor skill and dexterity (Cummings, 2007). Today, this medium includes devices that facilitate body movement, so called Multimodal interfaces. Multimodal interfaces differ from previous human-computer interfaces as they attempt to erode the artificial nature of interaction by facilitating actions resembling the 'real world' behaviour (Rajendran, 2013). Dance pads or floor mats (henceforth floor mats) for example require users to stand upright and move their feet between a set of marked padded squares. By doing so, these devices afford the opportunity to study the effect of coordinated action on cognitive processes. This is area of discussion that has witnessed renewed interest in the cognitive sciences under the banner of *embodied cognition*.

Embodied cognition is a theoretical perspective that conceptualises the act of thinking as coactivation of processes governing the body, environment, and neural processes (Wilson, 2002). To this view, the language that we use (Lakoff & Johnson, 1980), our mood (Proffitt, 2013), and recently, the way we interact with technology (Lindgren & Johnson-Glenberg, 2013) is grounded by prior sensorimotoric experiences. In other words, behaviour and thought are inextricably tied to one another. Thus, this theoretical lens provides the ideal framework to assess the impact of modern movement based technologies, like multimodal interfaces, on thinking.

Importantly, the current generation of children are going to experience this highly digital environment. Thus, the study of embodied cognition is important from a developmental perspective, as it provides a window in to the information processing style, and learning of future generations in several domains; be it school, at home, or while practicing for an extra-curricular activity (e.g. using the Nintendo Wii to improve physical fitness). Presently, there is a concerted effort to understand the factors that influence the development of children's EF. This is because EF are a set of cognitive skills said to underpin controlled behaviour, and careful thinking, with high levels of EF associated with academic (Blair & Razza, 2007), social (Riggs, Jahromi, Razza, Dillworth-Bart, & Mueller, 2006), and lifelong outcomes (Moffitt et al., 2011). At a conceptual level, both

the theories of embodied cognition and EF are similar in that they stress the importance of the motor system and coordinated movements to thinking. So, here I aimed to shed light on this relationship the purpose of both determining the impact of technology on children's cognitive development, and on a theoretical level shed light on the relationship between embodied cognition and EF.

The experiments created for this thesis bore resemblance to videogame technology, but took inspiration from classic neuropsychological tests of EF (e.g. the Towers of London and the Flanker task). To test the theoretical position of embodied cognition, each task was completed using a traditional user interface and a floor mat. Because the type of interaction and motor control requirements differed significantly between each device, I argue that drawing comparisons between them offer a means to extrapolate the relationship between embodied cognition and EF.

To begin, this thesis sets the scene by commenting on studies and commentaries of children's interaction with technology. As the added sophistication of digital technologies brings more embodied forms of interaction, this section is followed by an overview of embodied cognition theory, and the research of children's embodiment. Having discussed the view of embodied cognition I then move onto the theory of EF. In this final part of the review I introduce the main EF findings in the developmental literature, and explain why the theory blends conceptually with the principles of embodied cognition. Here, I also speak about the limitations of the current approach to studying children's EF, and suggest that tasks take inspiration from the environment children experience.

Thereafter, I describe three empirical studies testing the implications of embodied cognition to children's EF. The first two studies examined children's planning, using a newly developed videogame like task – *Slippy's Adventure*. After running the experiment for the first time I decided to make some modifications and run the experiment again. The findings revealed that children's planning was equally proficient between the floor mat and the keyboard. However, whether the task represented a test of embodied cognition is discussed. Interestingly, children's previous experience with videogame technology, and perceptual reasoning skills did affect performance. The implications of these findings are discussed. In the last experiment children completed a modified version of the flanker task. Once again, the findings from this study found that children were equally good at the task with each device: although it should be noted that the general pattern of performance between experiment 1 and 2 signified processing benefits while using the

floor mat, but not at a statistically significant level. Importantly, it appears that the stimulus presentation can have a significant effect on children's inhibitory processes, as a videogame like format caused a general improvement for the sample.

To finish, I discuss the findings in relation to children's interaction with technology, embodied cognition and EF, and offer future research recommendations. The limitations of the approach are also discussed.

CHAPTER 1 – CHILDREN, TECHNOLOGY AND EMBODIED COGNITION

In Steven Spielberg's 2002 sci-fi thriller Minority Report, the lead character John Anderton has the rather complex task of piecing together information related to future events, to determine if a crime will be committed. He does so by pinching and grabbing a set of virtual monitors, twisting and weaving his hands as if he were making a work of art. Gradually, he unravels the mystery by constructing a linear set of events from the disparate chunks of information displayed on a virtual interface. One cannot help but feel that his success reflects both his skill as a detective, and the flexible nature of the interface which he solved the crimes with. Fast forward to 2016 and Spielberg's vision of a super computer has become a reality, in the form of multimodal computing. Devices such as Microsoft's Kinect facilitate body movements, including whole body movements and gestures, thereby allowing the user to interact with digital technology in a body-based manner. And, as technology progresses these multimodal devices are becoming more ubiquitous in the domains of commerce, education, work, and leisure. From a research perspective, the current interface revolution is of interest as changing the way people interact with technology could have significant psychological implications. Consider for example the difference between the classic user interface – a keyboard and a mouse – and a multimodal interface, such as a touchscreen. If you wish to select an item on a desktop using the former, you must direct a mouse cursor to the desired location and click the left mouse button. With a touchscreen, the number of actions required to perform the same task is much less. Applications are immediately accessible via a single finger press. So, it could be argued that multimodal interfaces support a more direct and intuitive form of computing. This is not surprising given that *we design digital technologies that support our functional needs*,

"What the human brain is best at is learning to be a team player in a problem-solving field populated by an incredible variety of nonbiological props, scaffoldings, instruments, and resources. In this way, ours are essentially the brains of natural-born cyborgs, ever-eager to dovetail their activity to the increasingly complex technological envelopes in which they develop, mature, and operate." (Clark, 2001, p.219)

These 'non-biological', 'scaffolds', 'instruments' and 'resources' today represent the different digital technologies that populate our world. Rather than drive to and search a library for a book you wish to read, you can instead download that very same book onto an e-reader instantaneously from the comfort of our home, and proceed to turn each page

by swiping your finger across a screen. This is just one example of how the age we live in has changed the way we act in our environment. Information is more accessible than ever before, with Google effectively providing a library of information from anywhere so long as you possess an internet enabled device. It is changes like these that have led some to argue that children's cognitive development will be quite different. Prensky (2001) asserted that anyone born after 1980 could consider themselves a 'digital native', as their upbringing would take place in a technologically advanced age, and one that technology was readily available. He argues that the education system in the US is starting to see the repercussions of this change as on average children spend 5,000 hours reading compared to 10,000 hours playing video games and 20,000 watching TV. He comments that there is now a level of disconnect between how pupils are taught in the classroom, compared to how the access information independently,

"…are used to the instantaneity of hypertext, downloaded music, phones in their pockets, library on their laptops, beamed messages and instant messaging. They've been networked most of all their lives. They have little patience for lectures, step-by-step logic, and "tell-test" instruction."

Prensky (2001, p. 2)

With respect to children's cognition, Prensky argues that digital natives are more attuned to multitasking, and that this phenomena affects all children brought up in this age. As he highlights in the above quote, the accessibility and rapidity of informaiton transfer on digital devices affords children the opportnity to multi-task and consume information in short rapid periods. In contrast to digital natives 'digital immigrants' – the educators and parents of this digital generation – have been brought up learning and consuming media in a very different way. And so, Prensky argues that this has created a rift between the styles of learning shown by students, and the epxectations of the tutor of the tutee. Prensky's work is supported by his development and research of game-based learning. In recognition that many engineering students were struggling to learn to use the primary software package for their course (AutoCAD; Computer Aided Design), Prensky developed a game designed to teach students the functionality and application of this software. The game 'The Monkey Wrench Conspiracy' is a first-person simulation game whereby users play the role of an inter-galactic secret agent whose goal is to rescue a space station from an Alien attack. To do so, the player must find object to design and construct tools to progress through the game. The process of designing and constructing

takes place in a CAD like environment, thereby offering players the chance to familiarise themselves and learn to use the tool in a game setting.

The claims made by Prensky although timely are predominantly anecdotal and lack empirical validity (Bennett, Maton, & Kervin, 2008). Contrary to Prensky's assertion that digital natives prefer multitasking, a recent study found that using a laptop in the classroom is detrimental to attention and learning, resulting in poorer grades relative to peers learning without a laptop (Zhang, 2015). So, the idea that children's cognition has been dramatically transformed by the digitisation of the environment can be considered hyperbole. A more pertinent point to draw from Prensky's claims is that the behaviours and hobbies of future generations should become the focus of research to properly understand their development. Psychologists, educators, and academics in other disciplines are obligated to adapt their understanding of child development to include the activities that involve digital technologies. One such activity that has grown in popularity over the decades is gaming. And, although the number of investigations grow in this domain, gaming - as I will discuss – is an activity that has taken on new formats in recent years.

Video games and cognition

Video and computer games (henceforth video games) are a popular pass time of the current generation. Video games, like other types of games are structured around a set of rules. Player's initial interactions are guided and steadily withdrawn, to provide a more independent experience. Gaming is the activity that can be isolated, with peers, or part of the online community. A recent survey found that there are 20m people between the ages 6-64 play video games in the UK (Interactive Software Federation of Europe, 2012), 16% of the gaming population aged between 8-15years (Internet Advertising Bureau UK, 2014). Video games popularity lies in their ability to engage the player's interests, to entertain, help unwind, and offer a means to change and manage emotions (Durkin & Aisbett, 1999). From a theoretical perspective, studies of video games have demonstrated that this medium can engage users in a meaningful, and potentially useful way by providing a stimulating form of visual processing, that motivates further interaction.

One paradigm often adopted in the domain of video games is to compare the cognitive processes of individuals whose gaming routines differ significantly. Studies of

expert and novice's gamers show that certain types of games can enhance specific perceptual skills, such as the ability to recognise changes in visual stimuli, or selective attention (Green & Bavelier, 2003). Moreover, children with developmental disorders, marked by specific impairments in EF (e.g. ADHD; Attention Deficit Hyperactivity Disorder) show a similar level of commitment to video games as their typically developing peers, a finding that is somewhat converse to their cognitive profile (Bioulac, Arfi, & Bouvard, 2008). Investigations of the relationship between EF and video games have hinted that extensive game play can have selective EF benefits such as improving mental rotation (Boot, Kramer, Simons, Fabiani, & Gratton, 2008), and reducing inhibition response time (Castel, Pratt, & Drummond, 2005). A significant limitation of this research is that most of the samples investigated are of adolescents and adults. This is surprising given the number of video games available to children, and the indication that 16% of gamers in the UK are aged between 8-15 years. So, although the research indicates certain cognitive skills can be trained by gaming, the extent that these effects would be witnessed in children is questionable. One method to determine whether children's cognition is affected by gaming would be to develop cognitive assessments in a game-like format.

Cognitive assessment inspired by video games

Video games are highly structured, rule based problem solving environments. Progress in a videogame is mediated by the player's ability keep these rules in mind, think creatively, and problem-solve. Games designed for children will often include a varied colour palette, animations, sounds, and necessitate some form of learning. It is surprising that this media is not used to inform the development of cognitive assessment. Doing so could potentially improve the accuracy of assessment by adopting a format children are familiar with, and because of their flexibility, video games offer the chance to create highly structured cognitive tasks. To date, much of the research in the field of developmental psychology has borrowed tasks from adult neuropsychology. Although this body of research has helped to identify many cognitive skills that mature over the course of development, and the differences that emerge in developmental disorder groups, the tasks they use do not fit the context of digital native's development. Context is crucial to the assessment of children's cognitive abilities. Durkin and Blades (2009) summarised the status quo,

"…it does not make sense to detach the study of young people and the media from the study of young people per se. The bolder point is that the reverse holds too: it does not make sense to detach the study of young people from their interactions with the world in which they live. Whether we like it or not, that is a media dominated world, with the advent of new and cheaper technology, and the spread of that technology to every part of the globe." (Durkin & Blades, 2009, p.6).

The second point is that videogame technology differs from other media forms in that the user (or *gamer*) is an active participant in the story. Unlike movies, video games provide the ideal platform to understand both behaviour and cognition, as they can be viewed as a window to the decisions and action players make in simulated environments. This added factor of interactive engagement means that video games are stand-alone from other media forms where the user passively observes content, and is guided by the author/director's vision. Thirdly, digital technologies are here to stay, and as a species we will learn to adapt accordingly. Consider that 2,500 years ago, Socrates feared the institutionalisation of printed text posed a threat as he considered written words inadequate for teaching purposes (Plato, 2008), it is time we embrace the benefits of digital technology.

I have put forward a case to support the use of video games as a cognitive assessment tool. Parallel to the growing popularity of video games has been the creation of more immersive gaming environments that allow players to simulate real world actions. The development of multimodal interfaces has changed the way people interact with technology, and in the context of video games. Games played with these devices can be considered embodied problem solving environments.

Children's cognition and multimodal interfaces

Multimodal interfaces are peripheral devices that allow users to interact with technology through multiple sensory modalities, such as touch, sound, and sensorimotor action, thereby offering a perceptually rich interface between mankind and machine (Oviatt, 2003). The implications of multimodal human-computer interaction are promising because research suggests that these interfaces are preferred to devices that only permit a single input modality. For example, a mouse and keyboard interface require fine motor movements from the hands. Multimodal interfaces on the other hand provide

greater flexibility and consistency, and a communicative platform capable of meeting specific verbal and non-verbal behaviours for the user (Turk, 2014).

Multimodal technologies are still relatively new but are steadily becoming augmented with numerous forms of digital technology, thereby changing the user experience. Rather than passively observe content presented on screen users can actively participate in the virtual environment by swiping their fingers, moving their limbs in the coordinated manner, and vocalising instructions. For example, Microsoft's Kinect 2 sensor is capable picking up the user's body position and translating subtle movements into a meaningful action. In first person shooter (FPS) games such as Battlefield 4 the player can physically lean to the left or right whilst sitting on their sofa, to look around corners in the virtual environment. This added sense of embodiment is interesting because players can physically assume the role of the virtual character. Prior to the release of more technologically sophisticated multimodal interfaces, other peripheral devices encouraged body movement and embodiment by necessitating the use of the user's limbs, balance, and motor coordination.

Floor mats

Digital floor mats (also known as Flitter decks) require the user to stand on a set of marked squares, and move their feet between each square to match the demands of an onscreen challenge. Popularised by the music videogame Dance Dance Revolution (Wikipedia, 2016), dance mats were originally developed to get gamers up and dancing, by moving their feet between the marked squares to the rhythm of a song. Traditional mouse and keyboard interfaces draw upon fine motor skill and dexterity, whereas dance pads test the users gross motor skills and limb coordination. Hence, floor mat interfaces support whole body interaction, involving the legs and arms, more so than a traditional mouse and keyboard interface. Despite their simplicity, dance pads elicit a similar range and form of body movement to modern multi-modal interfaces. Like Microsoft's Kinect facilitates movement of the user in every direction, Dance Pads also offer this type of engagement – the difference being that the latter has a material point of reference in the form of a directional arrow. It is conceivable that this technology remains a popular household item - especially for augmentation with games consoles – because they support a form of interaction that users find genuinely fun and interactive. Nintendo's 2011 Wii console also supported use of a dance pad. Additionally, dance pads are a very safe interface, recommended for use of children above 3 years of age. Case in point, the study

of modern technologies, and their effect on children's learning I argue should entail consideration of the technologies children encounter, and the form their interactions take. As stated, video games are a popular pastime for children, and the interfaces they use are moving toward a more physical format. Thus, Dance pads offer the chance to study how future and present technologies will shape children's cognition. But what are the implications of body-based computing on cognition? Why is it that John Anderton could so seamlessly piece together fragments of a future crime? A recent line of enquiry in the cognitive sciences explores the possibility that the popular notion that *cognition is the act of neural information processing* is incorrect. An alternative, brain, body, and environment based account of cognition has caught the attention of the scientific community as it appears that thinking can be manipulated by sensory and perceptual processes. These theories of 'embodied cognition' therefore offer a lens to examine the effect of multimodal technologies on thought and action.

Embodied cognition

Broadly defined, embodied cognition is a set of theories discarding the traditional Cartesian conception of the mind (e.g. symbol processing) in favour of one that includes physical and environmental inputs. In other words, engaging thought, completing a task, and remembering to do something are all phenomena that require input from a range of sources acting in unison. Importantly, each of these sources relay information that is contextually relevant to the task at hand. For example, recollecting fond memories of a holiday may bring back imagery of the beach, as well as the sensation of sand against the soles of your feet and the sound of the swell crashing against the rocks. Essentially, theories of embodied cognition provide a richer interpretation of thinking by carefully considering the various body-based and environment inputs that constitute experience.

Presently, several proposals fall under the umbrella of embodied cognition including 1) cognition is situation dependent; 2) cognition is temporally constrained; 3) cognition can be offloaded to the environment; 4) our surroundings are a part of cognition; 5) action is sub-served by thinking; 6) offline cognition is body-based (Wilson, 2002). While each of these proposals have provided insight to potential embodied processes, I will discuss those that are pertinent in the domain of multimodal interaction, namely points 3 and 6. Point 3 is important for the following discussion as multimodal interfaces enable users to offload cognitive resources by sharing them between the brain and the environment (this topic will be discussed in more detail later). Point 6 is pertinent to the

following discussion as this thesis examines EF, a skillset that is arguably offline in nature. The ability to inhibit incoming sources of visual information for example is a skill that naturally guides our attentional resources without much conscious effort (Banich, 2009). Importantly, embodied cognition offers a theoretical framework to extrapolate the processes that underlie decision making when decision is made in a sensorimotoric way. In the following section I examine the literature that inspired theories of embodiment, to ground the key principles of the theory, and to critically review its contribution to the present understanding of thinking. One of the earliest indications that cognition could be considered embodied came from Jean Piaget.

Piaget, motor schemes and infant embodiment

Although theories of embodied cognition have steadily gained popularity since the 1980s, origins of the theory can be traced thirty years prior to Jean Piaget's studies of infant interaction. As part of his developmental stages theory, Piaget proposed that infant's interactions with the environment and their care-giver demonstrated that they understood the world in a sensory and motoric way (Piaget, Cook, & Norton, 1952). During his proposed 'sensorimotor period' of development (from birth to 24 months) Piaget noted that infants steadily graduate from initially reflexive, non-purposeful body movements to more controlled deliberate action. Piaget noted for example, that infants steadily modify their mouth shape during breast feeding to optimise consumption. In doing so, infants show awareness of their bodies capabilities, such that altering their mouth shape manner can help them achieve a desired goal. To Piaget, this behavioural maturation signified the development of motor schemes: action-outcome contingencies whereby infants associate an external behaviour with specific outcome. Over time, Piaget argued these motor schemes not only grow in number but also in complexity, such activities once requiring overt physical action could be executed at the representational level. In the above example, infants learn to associate the act of sucking with being fed, and so, the action represents more than the just the act itself. Research supporting Piaget's claim that infant cognition is sensorimotoric has looked at infants' propensity the interact with their environment, and to favour elements of a task that are goal-related. From this line of enquiry, if infant cognition is embodied, then infants should readily seek opportunities to explore their environment through the sensory modalities (e.g. touch).

As such, Needham, Barrett, and Peterman (2002) studied infants' motivation to interact with objects after artificially enhancing their ability to explore the environment. In their experiment two groups (treatment and control) of infants were first given time to play with some toys. The treatment group were given a Velcro glove that afforded them more opportunities to pick up and interact with the toys, while the control group interacted with their hands. After this initial pre-test play session both groups propensity to interact with objects normally (i.e. without interactive aids) was recorded. Children who had worn the glove pre-test showed an increased frequency of interactive behaviour, averaging 7 'swats' of toys to the control groups 5. The authors argue that this increase in the average number of swats represents a boost in exploratory behaviour, and consequently, their motivation to learn about the environment. Further, the authors note that this increase in exploratory swats was also associated with an increase in goal-directed visual attention, precluding the possibility that the glove simply altered infant's proprioceptive capabilities. From an embodied cognition perspective, the work supports Piaget's claims that one of the main drivers of infant's cognitive development is their sensory and perceptual experience. Indeed, recent studies have demonstrated that children draw on conceptual metaphors (Lakoff & Johnson, 1980) to create a better understanding of the principles underlying mathematics.

Abstraction and action

In school children are taught to count using a variety of physical tools such as an abacus, as well as pencil and paper materials. These learning materials help children to learn and develop their understanding of number and appear to draw on early conceptual metaphors. There is increasing evidence to suggest that materials used to support children learning of number support the metaphor *number as a collection of objects* (Lakoff & Núñes, 2000). To demonstrate this, Manches, O'Malley, and Benford (2010) asked children to split whole numbers into all possible constituent pairs (e.g. 7 into 3 and 4; 5 and 1; 7 and 0 etc.). The experimenters studied two modes of presentation: children completed the task solely in their head, and at another session on paper with a set of blocks, each to represent a constituent part of the number. The findings indicated that children were more proficient at partitioning the number into its constituent pairs when afforded the opportunity to physically split the number using a set of blocks. Thus, the findings suggest that affording children to act upon the conceptual metaphor (that a number is a collection of objects) improves their understanding of the problem. So, there

is an indication that children's conceptual understanding of a task is enhanced when interaction with the subject can be 'hands on'. Research has also shown that improvements can be witnessed even when the action is represented internally, or simulated.

Action simulation and action congruency

Many embodied cognition researchers highlight the importance of action simulation to the development and utilisation of certain cognitive skills. Action simulation is the act of mentally running a simulation of events to prime anticipatory processes, such as specific goal directed actions (Avenanti, Candidi, & Urgesi, 2013) and aspects of social-cognition, to ensure a more fluent conversation or interaction (Gallese, 2014). In doing so, the perceiver can make safer predictions for future actions, interpret the actions of others more effectively, and learn about how to act in certain contexts. Action simulation is related to the neuropsychological work on Mirror Neurons (Rizzolatti, 1994). Mirror neurons are part of a neural network shared between the pre-frontal, parietal and temporal cortical regions. The term 'mirror' is used to reflect the neural activation expressed when an individual executes a certain action (e.g. kicking a football) and during the observation of the same action (e.g. watching a football player take a penalty kick). The presence of mirror neurons in primates and humans (Cook, Bird, Catmur, Press, & Heyes, 2014) suggests a shared mind-body mechanism, whereby actors and observers draw upon the same cognitive model for action. For example, if I kick the right side of a football with the inside of my right foot the likely outcome is that the ball will travel from right to left. If I was to observe a football player making the motions to execute the same action (e.g. opening their right foot and swinging their leg behind the right-hand side of the ball) then I can predict the type of contact to be made with the ball, and the direction it will travel.

Considering mirror neuron research, investigators have tested the idea that thinking involves simulating actions, by manipulating the information that is presented to participants prior to action execution. An experiment investigating the role of the body during the processing of language participants were asked to read a set of sentences and determine whether they made sense or not (Glenberg & Kaschak, 2002). Reponses were executed by either pushing or pulling a lever. Each sentence contained a word that primed directionality of movement. For example, the sentence 'Close the drawer' contains a word

congruent with the action of pushing away from the body 'close'. Glenberg and Kashak manipulated the condition of both sentence prime and response action to include actions that were either congruent or incongruent to the sentence verb. The results demonstrated that when participants responded with congruent actions their response time was reduced. Thus, Glenberg and Kashak (2002) argued the finding demonstrates the embodied nature of language processing as participant's physical experiences in the world (e.g. that doors are often opened by pulling the handle toward oneself) reduced the tasks processing demands. Therefore, language is interpreted in relation to experience of actions made in the environment. Another embodied mechanism shown to mediate children's understanding is sharing cognitive resources between the brain and the environment, what is known as offloading cognition.

Offloading cognition

Offloading cognition is seated in the conceptualisation that cognition as a limited pool of resources. Acting on, and manipulating objects in the environment serves to offload cognition. In other words, offloading cognition allows the cognisor to share cognitive resources, or 'lighten the load', between the mind, their body, and the environment (Goldin-Meadow, 2001; Risko & Dunn, 2015). However, offloading cognition is not an activity that takes place under every context. Effective cognitive offloading requires knowledge of the problem, including the properties of the environment that will help solve the problem, and the desired end goal (Martin & Schwartz, 2005). In this respect, educationalists have argued that the learning materials children use at school must be related to their prior sensorimotor experiences both in and outside the classroom (Pouw, Van Gog, & Paas, 2014). For example, during writing this thesis I have taken notes on paper, drawn diagrams on whiteboards, and used sticky notes to help offload knowledge, and organise my writing. Without these external aids, I would not have a physical space to share my thoughts between my mind and the environment.

To demonstrate the effect of cognitive offloading, Martin and Schwartz (2005) conducted a series of experiments investigating the benefit of physical interaction with manipulatives on children's understanding of fractions. Manipulatives are physical objects used to support children's understanding certain principles (e.g. blocks and counters in mathematics). Children aged 9 and 10 years of age were given a set of operator problems, such as "make a ¼ of 8". In one condition, children worked on these problems using manipulatives (pie wedges). In the second condition, children were given a paper

and pencil equivalent (a picture of pie wedges), and were required to draw a line around a collection of objects on the page. Children's performance was judged from their verbal understanding of their solutions, and their physical/drawn arrangement of the materials. Martin and Schwartz (2005) found that children understood the operator problems better with manipulatives, and that this presentation was more conducive to number partitioning; splitting the collection of objects into smaller collections. However, the authors noted that children's frequency of object manipulation, did not correlate with successful verbal interpretations. In other words, children demonstrated a lack of strategic planning while manipulating objects. Although physical manipulation improved performance it was not directly associated with children's vocal recollection of their problem-solving strategy. Other work that has substantiated the claim for offloading cognition as a beneficial embodied process comes from studies of children's gestures. Gestures in a way include the same physical principles as object manipulation without the presence of an external stimulus.

In the last decade research of hand gestures has provided some useful insights into the relationship between body and mind. Goldin-Meadow (2010) argues that gestures are not just a communicative mechanism, but are a part of thinking. She cites several examples that demonstrate people's use of gesture for purposes beyond communication; such as whilst on the phone, when we talk to ourselves, and that the frequency of gesture increases with task difficulty. Furthermore, it has been suggested that gesture can aid learning, by freeing up working memory load (Ping & Goldin-Meadow, 2008), or offload cognition. As such, O'Neill and Miller (2013) studied children's hand gestures while they completed the Dimension Card Change Sort Task (Zelazo, 2006); a test of the executive function (EF), set-shifting (more information regarding EF is provided in the following chapter). In the task children sorted a set of cards by a dimension (e.g. sort by colour, sort by shape). The rule that underlies sorting is changed implicitly by the experimenter so that children must update their sorting strategy independently. O'Neill and Miller (2013) examined the degree that physical engagement influenced children's performance, by studying 2-6 year old's tendency to use hand gestures both during and after completing the DCCS (Dimensional Change Card Sort; Zelazo, 2006). It was found that both the frequency and accuracy (extent which the gesture matched the sorting rule) of hand gestures had a significant positive effect on switching performance. Specifically, children who made more spontaneous hand movements to assist their sorting decision were better sorters than their peers. Further, children who could accurately imitate the sorting rule with their hands (e.g. shape their hands like a rabbit) sorted more cards correctly to those

who produced arbitrary hand movements. So, in this case, the body provided an extra resource to offload information. The indication that task performance was improved by the inclusion of gesture suggests that the cognitive processes required to switch between sorting types were enhanced by the addition of a physical representation.

Cohort studies have also shown that children's gestures are a predictor of EF. Kuhn, Willoughby, Wilbourn, Vernon-Feagans, and Blair (2014) conducted a longitudinal study of 1,117 children's language, gesture and EF from age 15 months to 4 years. At the first assessment session (15 months) children's caregivers completed a checklist of their child's communicative gestures. Also, researchers reviewed 10mins of video data of each child working through a picture book with the caregiver. This additional measure provided another indication of children's communicative gestures. At 2 years of age children's EF was assessed using a set shifting task (Three boxes test) and a delayed gratification task (Snack delay task). At age 4years, children's EF was assessed using tests of working memory, inhibitory control, and attention shifting. Using structural equational modelling, Kuhn et al., (2014) showed that children's early gestures predicted later EF performance at age 2 and 4 years, after controlling for other possible contributory factors. Thus, evidence continues to grow demonstrating that children's EF is linked to the way that they physical represent concepts with their hands (i.e. by their use of gesture). Additional physical representations are commonplace in the classroom. The implications of embodied cognition have also yielded important findings from educational research.

In sum, I have reviewed some of the physical and sensory processes that influence cognition. Research of embodied cognition has shown that interactions with objects in the environment are an important part to infants growing understanding of the world and their own minds. Conceptual metaphors, such as 'number as a collection of objects', aid children's ability to ground key principles in mathematics. Studies of action simulation demonstrate that the quality of a movement can shape and enrich the cognitive models thinkers draws upon in the decision-making process. While studies of cognitive offloading indicate that the process of thinking can be considered a shared activity between the body and the environment. These embodiment effects did not occur serendipitously, but instead, highlight the complex interaction between behaviour, and how behaviour is mediated by internal and external factors. Digital technologies arguably exemplify this move toward an embodied interpretation, as devices for gaming and work leverage human sensory and perceptual processes. It is standard practice for a videogame console to be bundled with a multimodal interface (e.g. Microsoft's Kinect). More

importantly, these are the digital technologies that this generation of children will be using. So, the following section discusses children's interaction with technology, with specific reference to videogame technology and multimodal interfaces.

Psychological research with multimodal interfaces

Dance pads have been used to test a variety of cognitive skills, particularly those skills thought to be mediated by motor or embodied processes. Influenced by work demonstrating the presence of a spatial left-to-right ordering of number magnitude, with smaller numbers represented on the left (Dehaene, Bossini, & Giraux, 1993), Fischer, Moeller, Bientzle, Cress, and Nuerk (2011) sought to encourage the development of this spatial representation by training children to estimate number values using the left and right buttons of an electronic floor mat. While using the mat, trials were projected onto the floor, and children had to respond by using their feet to stand on either the left square to say that the trial number was lower to a position marked on a number line, or to the right to say it was larger. The same training was also completed in an analogous tablet PC presentation. After training, possible transfer effects with other numerical competencies were examined (e.g. counting). Training on the electronic floor mat provided greater improvements in numerical competency, more so than the tablet PC training. Therefore, the use of the floor mat developed children's spatial representation of number, by requiring them to make direct associations between body movement and mental representations of a problem.

Recent studies of interaction with the Kinect's on cognitive performance suggest that this device supports this embodiment process. Chao, Huang, Fang, and Chen (2013) asked two sets of participants to remember action phrases (e.g. "Roll the ball"). The first group simulated the action of each sentence using a PC keyboard and mouse. For example, the roll the ball would involve grabbing and dragging the ball using the mouse and mouse buttons. The second group were asked to physically act out the action phrases using a Kinect gestural tracking device. Participants who took part acting out the action phrases with the Kinect demonstrated better recall of the action phrases relative to the PC group. These recall effects were also better a week later. Hence, performing a congruent action with a multimodal interface facilitated participant's memory for action phrases more so than a traditional user interface. This suggests that information is retained to a better degree when participants simulate the action at the time of processing.

17

The creation of exergames – a portmanteau of 'exercise' and 'gaming' – has provided a paradigm to study the relationship between gross motor control and cognition. And as such, studies of adolescent's physical activity and EF have further indicated that gross motor control plays an important role to cognitive processes. In their study Staiano, Abraham, and Calvert (2012) examined the parallels between performance on Nintendo Wii's Sports Active exergame and a battery of EF tests; the Delis-Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001). Participants in an experimental group completed the EF battery either side of a 10 week exergame training program. This training group was split into two types of training, competitive and cooperative. A control group did not participate in the training program. The results of exergame training yielded significant improvements in EF task performance for participants in the competitive training program, comparatively to the cooperative training and control groups. So, although gross motor control training appeared to improve EF, the conditions under which gross motor control is encouraged also influences the rate of improvement.

Summary of children's cognition and multimodal interfaces

In this section I discussed the potential psychological processes active while using a multimodal interface. It is evident that the environment children are brought up in today is quite different, and as technology progresses so too should our ideas about cognition. Computer games are a popular medium for children of all ages, and should not be overlooked in terms of their learning and growing understanding of the world. From a psychological perspective, video games are the ideal platform to study cognition as they are progressive, rule based, and rewarding. The literature of embodied cognition implicates the existence of certain embodiment mechanisms. Each embodied process is supported through multimodal interaction. And, as the evidence base increase, it appears that children's understanding of the task is improved when they complete it in an embodied manner. However, there are still a myriad of cognitive skills yet to be investigated in the context of multimodal interaction. One cognitive skill that has received a lot of attention in the developmental literature is executive functioning (EF). In the following chapter I will review some of the literature on EF to highlight its developmental importance, and to draw parallels with the theory of embodied cognition.

CHAPTER 2 – EXECTIVE FUNCTIONING AND DIGITAL TECHNOLOGY

The process that guides decision making, innovation, and creativity has been of great interest in the field of psychology. Each of these skills are said to be underpinned by an individual's executive functions (EF). Broadly speaking, EF are defined as the cognitive skills that manage and coordinate thought and behaviour, especially when attempting to solve a novel problem (Hunter & Sparrow, 2012). People engage EF when creating something novel, like painting a picture, and when solving problems by adapting previously successful solutions, such as applying knowledge of engines to start a lawnmower, having previously kick-started a motorbike. From a developmental perspective, EF emerge and mature from as early as the first year of life (Diamond, 2013) and continue to develop through formal education (Lee, Bull, & Ho, 2013), and into adulthood (De Luca et al., 2003). The complexity of EF development is evidenced by spurts of progression rather than linear simultaneous improvements across the core EF skills (Anderson, 2002). It is because of this non-linear progression during childhood that the factors that influence children's EF has become a popular line of enquiry. Recent efforts have focussed on the impact technology has had on children's EF, in response to the growing recognition that the environment that children grow up, learn, and socialise in is quite different to previous generations of children (Schwartz, 2014). For example, many science museums now have pedagogical material presented in a visually stimulating media, augmented with multimodal interfaces that allow children to initiate learning at their own pace, encouraging a sense of self-discovery through a medium that is both interactive and engaging (van Dijk, Lingnau, & Kockelkorn, 2012). These environmental changes are altering the typical interactions children have with digital technology creating new platforms for them to learn, develop cognition and interact (Bennett et al., 2008). As EF encompasses a skillset proposed to underlie many everyday functions, including problem solving and learning, a focal point for this thesis is the effect that contemporary technologies (namely, multimodal interfaces and video games) have on children's EF. Thus, a good theoretical grounding of this skillset will provide a framework to determine the influence of technology. So, in the following section I begin by outlining a brief history of EF. I then discuss how the concept has been defined and modelled from empirical work. I then move on to critique developmental studies of EF, with specific focus given to the impact of technology.

The first documented case of EF deficit can be traced back to 1848, from the notes of the physician John Harlow and his patient a railway foreman, Phineas Gage. Gage was involved in an accident while planting dynamite into soil. One day during this task Gage became distracted and accidently ignited the dynamite while bedding it in a nearby hole. In the resulting explosion, the tamping rod shot up into Gage's cheek and exited out through his forehead, rupturing his skull and partially removing a section of his frontal lobes. To the shock of the medical world, Gage remained conscious after the event, and returned to work after two weeks in hospital. However, the story did not end there for Gage. John Harlow, Gage's physician, had documented some abnormalities over the course of his patient's recovery. He soon recognised that the accident had compromised Gage's cognition and functional capacities. Harlow notes that the foreman was no longer the man he once was,

"The equilibrium or balance, so to speak, between his intellectual faculty and animal propensities, seems to have been destroyed. He is fitful, irreverent, indulging at times in the grossest profanity (which was not previously his custom) …Gage was 'no longer Gage' [sic]."

(Harlow, 1868, p.5)

Post trauma, Gage was no longer the organised and reliable foreman he previously was. He was not as punctual, often irritable, and had fallen out of favour with his colleagues. Harlow recognised that post-accident Gage was less able to manage and regulate his daily activities. His behaviour was impulsive, showed lack of planning, indicating that he could no longer manage his thoughts. Since the seminal case of Phineas Gage much has been speculated about the associations between the frontal lobes, and the psychopathology of Phineas Gage. As well as playing an important role in the maintenance of an individual's personality it appeared that the frontal lobes facilitated the abilities that constitute an effective worker (H. Damasio, Grabowski, Frank, Galaburda, & Damasio, 1994).

Gage's case indicated that an important part of cognitive functioning is the ability to control and regulate thought. That is the essence of EF; the investigation of the composition, structure, and influencing factors that shape, govern, and mediate the capacity to regulate mental processing. As I will explain in the following section, the

pursuit of EF knowledge has given researchers some valuable insights to the developing brain, and the implications of EF to daily functioning.

Executive functioning definition

Broadly defined, EF are a set of high-level cognitive functions responsible for the control and regulation of cognition and behaviour, especially during activities that require novel problem solving (Hunter & Sparrow, 2012). The term 'high-level' has been describe EF as this skill set is proposed to involve a combination of complex activities such as reasoning, language, problem solving (Thagard & Aubie, 2008). In contrast 'low-level' cognition refers to sensory processes such as vision and touch. From a neuropsychological perspective, EF are said to be housed in the pre-frontal cortex, a cortical region with a long development period (Benes, 2001). Neurobiological studies indicate that the pre-frontal cortex plays a crucial role in the managements of incoming information from the environment. Perception, action and mental activity are governed by the pre-frontal cortex's role of activating and supressing other cortical regions (Knight & Stuss, 2002). With the indication that the neural substrates of EF experience a protracted period of development, as well as the capacity to allocate cortical resources from environmental stimulus it is of interest what EF constitute, and whether these abilities are part of an integrated, or independent system. A large body of research has attempted to classify the abilities that underpin EF, and by doing so, provided several models and components for an investigative framework.

Models of executive functioning

Two main approaches have been adopted in the conceptualisation of EF. The first, is to consider EF as a single, unitary construct made up of various sub processes. An example is Baddeley's model of working memory (Baddeley, 1986). Working memory can be defined as a set of processes that are responsible for the management of incoming perceptual information, including its selection and short-term storage, and transferral to long-term memory (Baddeley, 2010). In his 1986 model, Baddeley proposes that a central attentional system – what he refers to as the 'central executive' – manages the centres for perceptual input, thereby guiding the individual's thinking. From this perspective, the extent that an individual inhibits a response, such as pausing to think of what to say next

in conversation, is regulated by the central executive. Indeed, when the initial conversation between experimenter and participant is informal and contrived, working memory performance suffers (Nemeth, Turcsik, Farkas, & Janacsek, 2013). Contrary to Baddeley's emphasis on the central executive, Dempster (1992) argues that person's inhibition ability governs the activity of EF components and is pivotal to the maturation and development of EF. In his conceptualisation, Dempster (1993) characterised inhibition as a process of interference management based upon three dimensions: 'temporal' (i.e. the time that the cognisor manages interference online, be it prior to, immediately during or after stimulus presentation); 'formal', including sensory, perceptual and language input; and 'spatial' which included internal and external evaluations of the environments spatial features. Much of the evidence in support of the unitary view of EF has demonstrated that the reported model components correlated with one another, signifying a shared underlying process (Carlson, Mandell, & Williams, 2004). Also, developmental research shows that performance across a wide range of EF tasks improve almost in unison, particularly between the ages of 3- and 6-years (Carlson, 2005).

The second approach to modelling EF has been the componential approach. Componential models consider EF as a collection of independent and inter-related cognitive processes, that often work together to achieve a desired outcome. To date, the most influential componential model of EF has been the three-factor model proposed by Miyake et al. (2000). From this model switching, inhibition, and updating are the core EF skills. Switching is the ability to identify and select a different action. Inhibition is the ability to resist impulsive, learned (or habituated) response patterns when encountering both familiar and unfamiliar situations. Updating is the ability to hold new information in working memory while maintaining, or reiterating previously held information. Using confirmatory factor analysis Miyake et al. (2000) found these three skills to be distinct, but also moderately to strongly correlated. The authors stipulate that overlap between each component reflects the combinatory nature of these skills: the process of updating and switching are similar in application as both processes involve disregarding irrelevant information from the environment and avoidance of processing obsolete information. Further, Miyake et al. stated that a lack of behavioural inhibition would have a detrimental effect on higher level EF skills (e.g. such as planning).

Perspectives from studies of EF development

A recent investigation of the developmental profile of EF from childhood to adolescence found that, comparatively to adult EF, this developmental trajectory is quite uneven: some components develop faster than others. Lee et al. (2013) studied children's longitudinal changes in EF from ages 6 to 15 year olds in a sample of 688 children over a four-year period. Children's updating, working memory, inhibition, and switch efficiency (a skill conceptually like set-shifting) were tested once annually. Results yielded age-related improvements in working memory and updating, with an indication that these skills would continue to develop later into adolescence. Age related changes in inhibition and switching however were less clear cut, as results from their Flanker task (a test of inhibition) showed an increased accuracy but similar findings were not found on another test of inhibition; the Simon task. Thus, it appears that certain components of EF, namely inhibition, do not uniformly develop calling to question the factors that influence the maturation of this skill. Further, regarding the structure of EF, Lee et al. (2013) stipulate that it was not until around age 15 that their data supported a three-factor model. One possible explanation for these differences is that children's behaviour is still very much in the process of refinement. In the younger years, a person does not always have the luxury of experience to guide behaviour.

For instance, recent investigations of 'self-control' demonstrate that the ability to show restraint, and avoid impulsive decision making based on immediate attainment of a goal is a crucial factor across the lifespan. Moffitt et al. (2011) conducted a longitudinal observational to determine the significance of childhood levels of self-control and adulthood outcomes and achievements. 'Self-control' is arguably a term synonymous with EF, as Moffitt and colleagues, administered tests that tap the individual's ability to think carefully, resits impulse, and choose between conflicting task materials, e.g. delayed gratification, discounting, and intertemporal choice tasks. Their investigation of the factors that mediated participants (N=1,037) EF from age 3 years to 32 years of age Moffitt et al., (2011) found that reported levels of childhood EF positively correlated with the adult life outcomes of health, financial status, criminal activity, and substance dependence. In other words, children who showed higher levels of EF at age 3 years were more likely to be healthy, earn more money, less likely to be involved in criminal activity, and less likely to use drugs by age 32years. Clearly, the development of EF is an important predictive factor in the later-life outcomes of the individual. Research drawing links

between this skillset and academic outcomes also emphasises the developmental significance.

Blair and Razza (2007) for example studied the relationship between children's self-regulation, mathematics, and knowledge of letters. They compared children's scores on the Child Behaviour Questionnaire with performance on two tasks: 1) Luria's classic peg tapping task developed by Luria for patients with frontal lobe trauma (Luria, Karpov, & Yarbuss, 1966). In the task children are given a wooden dowel which the experimenter instructs them to tap on a table twice to respond if the experimenter taps once on the table, but to only tap once if the experimenter taps twice. Thus, the task is treated a test of children's inhibition; the ability to resist the impulse of repeating the actions made by the experimenter. The second task children were asked to complete was the item selection task (Jacques & Zelazo, 2001). Children were presented cards which they had to sort by one of four dimensions: shape, colour, size, and number. The sorting rule was changed implicitly and so, children had to demonstrate cognitive flexibility to switch between sorting dimension and cope with the changing nature of the game. Blair and Razza (2007) found that children who performed at the lower end on the EF assessments were those performing below average at mathematics and letter understanding. Seemingly, the ability to reject a pre-potent motor response and to shift set are cognitive abilities that are a part of the underlying cognitive architecture of two important academic abilities. Blair and Razza (2007) also stipulated that EF are more important for school readiness than IQ. Another line of research that has provided impetus to the study of EF is that of developmental disorders.

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterised by a triad of impairment in communication, social interaction and restrictive repetitive behaviours (American Psychiatric Association, 2013). Executive function (EF) difficulties have been reported in the condition since its first description (Gnanathusharan Rajendran & Mitchell, 2007). The restrictive repetitive element of the triad map onto atypical EF (Lopez, Lincoln, Ozonoff, & Lai, 2005). One of the first indications that ASD could be classified as a disorder marked by impaired EF came from Damasio and Maurer (1978). In their seminal paper, these authors describe the behavioural similarities between children with ASD and adults with trauma to the frontal lobes,

"What autistic children and patients with some frontal lobe syndrome seem unable to do is to teach themselves ways of adapting to modified environmental contingences." (Damasio and Maurer, 1978, p.781)

Damasio and Maurer (1978) alluded to autistic children's preference for repetitive behavioural patterns over adaptive behavioural change. For example, children with ASD will often choose to play with a toy car in a repetitive manner, such as rolling it forwards, without attempting to try new actions such as putting toy people in the car, or adding other elements to their play. Research of children with ASD's EF has shown that many EF skills are less developed, or show impairment relative to typically developing children of the same age and intelligence. For example, in the Towers of London task Children with Autism often make more rule violations (Robinson, Goddard, Dritschel, Wisley, & Howlin, 2009), take more time to reach the goal state (Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2004), require more moves to complete the task (Ozonoff & McEvoy, 1994) and take more attempts to succeed (Ozonoff, Pennington, & Rogers, 1991). Some have even gone so far to argue that ASD is a condition hallmarked by impairment of EF (Russell, 1997).

Another developmental disorder that shows deficits in EF is attention deficit hyperactivity disorder (ADHD). ADHD is a developmental disorder marked by the inability to sustain attention, high distractibility, poor organisational skills, and high impulsivity (Dalsgaard, 2013). Children with ADHD experience difficulties staying on task, organising their thoughts, and orienting their bodies in a goal directed manner. Because of this, children with the condition often struggle at school, where learning is achieved by perseverance, avoidance of distraction, and goal setting. Barkley (1997) proposed that children with attention deficit hyperactivity disorder (ADHD) show specific marked impairment of "behavioural inhibition". He suggested this deficit, the inability to stop and use knowledge selectively in the decision-making process has a detrimental cascading effect on other EF skills such as self-regulation of affect, inner speech, and working memory. Studies of children and adolescents with and without ADHD confirm that the condition both impairs EF, and, has a detrimental impact on the individual's academic achievement (Biederman et al., 2004).

Taken together, the research of EF offers a new perspective to view children's cognitive functioning. It is clear this skill set provides a template which children base their decision making and learning. Additionally, the difficulties EF impairments expressed in ASD and ADHD demonstrate the implications of EF from both a cognitive and behavioural perspectives. Children with ASD often find themselves trapped in behavioural cycles that deny them the ability to adapt effectively to their environment. In ADHD, the inability to inhibit behavioural responses means their actions are frequently guided by distraction and

fleeting thought. Consequently, dedicating time to a task, and to learn the principles of that task, is an activity that requires intense resistance to impulse. A commonality between each of the articles discussed above is that EF ability levels appears to mediate the child's behaviour. It is apparent that success at school, and later in society is determined by the capacity to channel information effectively at a cognitive level, and that this channelling permits a more informed decision making process. The child who can wait to receive a second marshmallow in the classic delayed gratification task is more likely to earn more money as an adult (Casey et al., 2011). The autistic brains preference for repetition is related to EF impairment. Thus, the narrative, both in the theoretical and empirical work of EF, suggest a decision-making model that involves both mind and body. Case in point, some EF scientists have considered the physiological process that may develop or mediate EF.

EF components of interest

Planning

      Planning is a higher order EF, in that other components are said to underlie its use (Miyake et al., 2000). Broadly defined, planning is the ability to mentally represent a sequence of events in the service of fulfilling a goal (Ward & Morris, 2005). Shopping for example is an activity that requires good planning. Ultimately, the aim of shopping is to re-stock shelves. Writing a list of the items that need replenished prior to leaving the house ensures shoppers know exactly what to purchase. Very careful planners may order this list in accordance with the layout of the supermarket aisles, to reduce the time they spend navigating the shop floor. The research effort of planning attempts to identify how the abilities of the individual and the problem affect the formulation and deployment of a plan. Models of planning from the field of artificial intelligence helped identify these factors (e.g. Anzai & Simon, 1979; Simon, 1975). Anzai and Simon (1979) suggest that internal (e.g. individual) factors included the ability to abstract, working memory, and information processing speed and storage. External variables included the problems search depth and environmental stimuli. These internal and external variables feed into the planning process: representing the problem, setting targets, formulating a logical sequence of actions to follow, carrying out those actions, and to process feedback post-execution to either continue with the current course of action, or modify the plan. Thus, information processing models of planning deconstructed the act of planning into composite skills: the ability to recognise task relevant information from the environment,

to combine this information with elements of the task to progress toward the desired end state, and to appreciate that some actions will not lead to progress and should be left out of the overall strategy. Developmentally, children's ability to plan mediates their academic achievement (Best & Miller, 2010), particularly for core domain subjects such as mathematics and reading (Bull, Espy, & Wiebe, 2008). So, it is of great interest how this ability matures, and the parameters that determine the success of a plan. Experimental work shedding light on this area often assesses children's planning using tasks like the Towers of London.

In the Towers of London task three coloured beads (red, blue, and green) must be shifted between three wooden rods of different lengths. The experimenter provides a desired end state configuration of these three pegs, with the starting position of the beads differing in accordance to the experimenters desired task difficulty. The rules of the task are that only a single bead can be moved at a time, that each peg can only hold its respective number of beads (e.g. 3, 2, and 1), and that each problem must be solved in a single turn. Shallice's task included four puzzles that could be completed in 2 or 3 moves, four that were 4 moves to completion, and four that required five moves. Performance on the Towers of London task is measured by initial thinking time (i.e. the time prior to executing the first move), completion time, number of moves to completion, and the number of rule violations made (e.g. putting a larger disk on top of a smaller disk).

Developmental studies of planning have shown that the number of moves required to complete a Tower configuration affects children's ability to plan, and to select the optimal sequence of moves. In Unterrainer and colleagues (2015) experiment 179 children were split into four age groups - 6-7years, 8-9years, 10-11years, and 12-13years – and completed Tower configurations that could be completed in a minimum of 3, 4, and 5 moves. A linear effect of age was found such that the older children were the more optimum solutions they executed (e.g. in the minimum number of moves possible). With respect to initial thinking times, children aged 6-years spent longer planning their first move, apart from 5-move configurations, whereby children aged 12-13 years spent longest thinking about their first move. Interestingly, the number of moves required to complete a puzzle is a factor often manipulated in video games, as well as other aspects intrinsic to the execution of a plan (e.g. attention switching, working memory) (Montani, De Grazia, & Zorzi, 2014). Another skill of interest in this thesis was children's inhibition.

<u>Inhibition</u>

Inhibition is an executive function defined as the ability to withhold a prepotent (or habituated) response to a stimulus. The skill was given attention by Shallice and Norman's (1980) model of attentional control. The model consisted of two competing processes that governed thought and action: routine, habituated behaviours that emerge from practice and learning, and a "supervisory attentional system" that governs behaviour in unfamiliar situations. The model suggested that decision making is a process that involves a cognitive mediator - the supervisory attentional system - that when faced with a familiar situation encourages problem solvers draw on prior experience to guide their behaviour. Conversely, in unfamiliar circumstances the supervisory attentional system directs the problem solver away from learned responses (i.e. inhibits habituated response patterns) in favour of a novel approach.

The question of what form this novel approach took however was somewhat problematic to the model. Indeed, Shallice and Norman (1980) conceded that problem solving is often not as simple as the identification of familiar and unfamiliar problem solving contexts, and so, suggested that the supervisory attentional system provided "contention scheduling". Contention scheduling was a process whereby every decision-making process (both familiar and unfamiliar situations) is informed by the prior knowledge. This knowledge is applied recursively until the problem demands reduce to an accomplishable goal. So, Shallice and Norman (1980) argued that all problem solving requires some degree of inhibition, as behaviours that appear seemingly routine require on the fly decision making.

The importance of inhibition to problem solving would later be discussed by Shallice in his seminal paper 'Specific Impairments in Planning' (Shallice, 1982), helping to promote the skill as an important part of executive functioning (EF). Shallice suggested that impairments of the supervisory attentional system would cause the individual to rely heavily on contention scheduling; an over reliance that was demonstrated by the inability to avoid distraction, perseveration of a previously learned response, and difficulties inhibiting extraneous, but familiar, environmental information. These behavioural impairments, Shallice stated, are often manifested by patients with frontal lobe trauma. Thus, inhibition was implicated as a part of the frontal lobes, the neural substrate of EF. Since the model proposed by Shallice and Norman (1980) and Shallice's follow up research of planning in frontal lobe patients, Inhibition has been considered a part of EF. Once again, research in the domain of artificial intelligence helped to develop cognitive

models of problem solving and EF. It was not until a decade later that inhibition became a research topic in the context of children's cognitive development.

Inhibition is a highly desirable cognitive skill during childhood as it helps children avoid distraction, stay on task, and to make rationale behavioural choices. It allows for a more careful, and deliberated decision making process. For example, pre-school levels of inhibition relate to academic performance as children enter primary level education (Bull & Scerif, 2001). Simplified infant and child cognitive assessments of inhibition demonstrate that suppression of a dominant response develops from as early as year one of life. It is not until between the ages of 3 to 5 years that the more complex process of inhibiting a response while presented conflicting stimuli emerges (Garon, Bryson, & Smith, 2008). Moreover, studies of developmental disorders have emphasis the significance of inhibition to children's behaviour and cognition. Since the growth of interest in disordered development, EF impairments have been identified in several developmental disorders including autism spectrum disorders (ASD), Tourette's syndrome, and attention deficit hyperactivity disorder (ADHD) (Pennington & Ozonoff, 1996). Regarding inhibition, the skill has become a skill of focus in ADHD. ADHD is a developmental disorder marked by the inability to sustain attention, high distractibility, poor organisational skills, and high impulsivity (Dalsgaard, 2013).

In its original composition, the flanker task requires participants to respond as quickly as possible to a target letter that has surrounding 'flanking' non-target letters (B. A. Eriksen & Eriksen, 1974). There are three conditions to the task, neutral, congruent and incongruent. In the neutral condition participants are required to respond to the target stimulus when flanked by stimuli from a different response set (i.e. stimuli that were not paired with the target stimulus in the instructions). In the congruent condition the target letter is presented with matching flanking stimuli (i.e. the same letter), or independently without flanking stimuli. In the incongruent condition participants are presented the target stimulus with flanking stimuli that are from a different response set. For example, Eriksen and Eriksen (1979) used the letters H, K, S, and C as individual target stimuli. In the incongruent condition, these letters could be flanked by the letters N, W, and Z. The documented 'flanker effect' is the elevation in participant's reaction time to the target stimulus in the incongruent flanker condition, relative to the neutral and congruent conditions. Eriksen and Shultz (1979) argued that the flanker effect is the result of conflict resolution, in that, the visual system processes and evaluates both target and flanker stimulus and therefore cannot avoid perceptual interference from incongruent flanking

stimuli in the decision-making process. Thus, adept performance on the flanker task is demonstrated by inhibition of the flanking stimulus in the incongruent condition. Performance in the task is measured by response time (RT) and accuracy (e.g. if an answer is correct/incorrect).

Developmental research using the flanker task has modified the stimulus presentation to account for the limitations in children's letter understanding, for example, by using arrows or pictures facing either left of right (e.g. 0 or 180° of the central fixation point). Altering the stimulus to create more child appropriate flankers task has yielded interesting results. Rueda et al. (2004) presented children two versions of their flanker task: one that the stimuli were angled brackets, and in the other stimuli were yellow fish. Correct responses on the fish version of the task triggered a reward animation, whereby the target stimuli (i.e. the middle fish) blew bubbles. In contrast, the arrow version of their task did not include any animations, but instead text momentarily replaced the target stimulus with the words 'Correct' or 'Incorrect'. These modifications to flanker presentation and response feedback has a positive effect on children aged 10 years' performance: they were faster and more accurate to respond to fish stimuli relative to the arrow stimuli. Arguably, their fish flanker task was more game like in its presentation, providing children a more colourful presentation, and a context relevant reward. These experimental manipulations were given consideration in the development of my own flanker task detailed later.

Caveats of the current approach to EF assessment

Many of the tasks used to assess children's EF (including those above) take inspiration from adult neuropsychology. And while this approach may have been suitable as researchers continued to develop a general understanding of EF, it is becoming more apparent that perhaps a more child-focused methodology be adopted. For instance, it appears that inhibition does not develop at the same rate as working memory and updating between the ages 6- to 15-years Lee et al. (2013). So perhaps inhibition is a sub process of EF that involves other neural substrates that are not yet well understood.

In his review, Anderson (2002) outlines the features effective of EF assessment, and the limitations of previously adopted methodologies. These include the novelty of the task, deriving meaning of scores attained, the tasks relatedness to real world problems (i.e. ecological validity). I argue that each of these points could be tackled by taking a

game design approach to task development. His first assertion argues that an EF task must tap the child's novel problem solving skills, and not allow them to fall back on practiced, learned behaviours. To give a real indication a child's EF ability the assessment must be new, challenging, and require the child to pull together various sources of information. In commercial games, children's progress is mediated by their ability to problem solve in new environments, and draw on the skills they have learned from the beginning. These challenges are often progressive; the more a player progresses, the more difficult the game becomes. The necessity to problem solve and combine knowledge from previous attempts means that children are frequently faced with novelty in games.

With respect to interpreting EF scores, Anderson states that claims about the specificity of a result should be cautious given the difficulty in delineating the different EF abilities, as often a task will tap several EF simultaneously because of the inter-relatedness of each EF facet. He also notes that researchers should be aware of the presence and utilisation of non-EF skills in the process of response generation (e.g. individual differences). Thus, predictions drawn from the data should consider other random variables that may contribute to the variance in the data. With respect to games, this would involve finding out children's game preference (e.g. platform games) and developing a task that fits their preference. By doing so, the experimenter would account for some of the individual differences that exist among pupils, and create an assessment tool that children can engage with as well as relate to. In the following thesis, I adopted a type of statistical analysis that considers individual differences (the random effect of participant), to generate more accurate interpretations of children's functioning.

Ecological validity is the extent that performance on a cognitive test reflects the individuals daily functioning. The neuropsychological evidence for the cognitive assessment of EF relating to everyday functioning in adults is mixed, with some studies (often using self or informant report questionnaires) reporting high levels of consistency between the patient's performance in the lab and in the home (Burgess, Alderman, Evans, Emslie, & Wilson, 1998), whereas other experiments adopting a similar methodology do not report this congruency (Amieva, Phillips, & Della Sala, 2003). Several reasons have been proposed for this apparent lack of ecological validity. Anderson (2002) states that the environment in which testing takes place is crucial to the generalisation of their EF abilities. Conducting the assessment in a familiar environment (e.g. at school) improves the experiments ecological validity relative to laboratory settings (Banich, 2009). Furthermore, the level of guidance and instruction provided should be minimal, given

that, if thorough, the experimenter runs the risks of artificially inflating the respondents score. It is possible that this practice is the reason why practitioners have commented on the discordance between the performance of a patient on EF tasks, and their daily EF functioning (B. A. Wilson, 1993). As such, the empirical work in this thesis was conducted on school premises.

Another method to improve the ecological validity of EF tasks is to build a profile for each participant from several sources (e.g. test scores from teacher, parents reports of social skills), to make certain that the response data to the task is consistent with other cognitive and social factors. As such, recent investigations have taken a more holistic approach to profiling patients by including variables that may not be possible to assess using traditional EF tasks, such as compensatory strategies and environmental cognitive demands. Experiments using this method have shown that these other non-EF skills can account for a significant portion of the variance from informant ratings of EF functioning (Chaytor, Schmitter-Edgecombe, & Burr, 2006). As will be discussed later in the thesis, parent reports of their child's technology use, and baseline cognitive assessments of EF were adopted in this thesis to build a profile of each child prior to testing.

Another aspect of ecological validity is the extent that the individual engages meaningfully with the task. A caveat of the current approaches using adult EF assessment tools is that researchers assume children's level of engagement to be equal to that of adults. However, given that these tasks were not designed for this age group, there is a high likelihood that they do not provoke the same level of interest and cognitive engagement, and therefore, yield spurious results.

"Adult derived tests may be of little interest or relevance to young children."

Anderson (2002, p.75)

Replicating adults test experimenters run the risk of creating tasks that children cannot relate to, or find the motivation to engage with meaningfully. Moreover, it could be that children's EF is quite different to the type manifested by frontal lobe patients, as this comparison often drawn is still not well understood. Indeed, some have argued that by simplifying adult neuropsychological tasks for children, researchers run the risk of developing a task without retaining the core principle of EF (Garon et al., 2008). Recognition that children's pass-times are often not echoed in neuropsychological tests has led some researchers to move away from traditional cognitive assessments of EF to more computer game like tasks, what has been termed 'Gamification' or serious games.

Video games are a popular form of entertainment to children and adolescents (Olson, 2010), providing users the opportunity to relax, play with others, learn, and challenge problem solving skills (Martinovic, Burgess, Pomerleau, & Marin, 2016). Thus, it has been argued that cognitive development can be better understood by investigating the potential of electronic games to teach and develop cognitive skills (Connolly, Boyle, MacArthur, Hainey, & Boyle, 2012), as well as inform educational game designers. Case in point, electronic games designed specifically, for non-entertainment purposes, or Serious Games, has become burgeoning literature in developmental psychology. Arnab and Clark (2016) state that,

"The power of games to immerse and motivate and the capabilities of games to foster and facilitate cognitive gain, awareness and behavioural change, have encouraged more games of this nature to be developed within a research context as well as to be deployed in real application settings."

Arnab & Clark (2016, p.1)

So, creating tasks that resemble video games, and not simply digitising the currently adopted tasks could be a fruitful avenue for investigation. As Arnab and Clark argue, this medium can immerse and teach users for potential behavioural change outside the laboratory. For brought up in a video game rich world, this means psychologists should be looking to this medium for inspiration and as a tool for cognitive assessment and intervention.

In this section I have discussed the different models of EF, and how they have been applied to the study of children's development, and the significance of EF shown by studies of developmental disorders. Importantly, the driving force behind experimenter's theoretical development in the field is the task that they use to assess it. Presently, there is a culture of adopting adult neuropsychological test and simplifying them for assessment with children. However, the circumstances which children may learn to develop EF may well be quite different to that experienced by adults. I critically appraise these tasks composition in terms of their relatedness to children's lives, and their ecological validity.

A step in the right direction: modern EF interventions

Within the last decade, the draw of computer and video games to young people has led some researchers to develop more game like EF interventions such as Cogmed.

Cogmed is a working memory training battery consisting of several mini-games presented with colour, animations, in a video game like setting. To achieve improvements in working memory, Cogmed collects statistical information about the user's progress and tailors their training schedule accordingly. For example, in one game 'Space Mines Patrol' players assume the role of a spaceship with the task of either avoiding obstacles, or collecting items. As players progresses through the game, these tasks   become increasingly more cognitively demanding, by the inclusion of sequencing – to collect items in a certain order – and to multitask each of the rules and skills of the game to complete a boss battle[1]. Cogmed is inspired by previously traditional cognitive assessments and modified by the augmentation of game characteristics: including an algorithm to adapt to ability level per performance, visual feedback, and a points system based on performance.

Thorell, Lindqvist, Bergman Nutley, Bohlin, and Klingberg (2009) assessed the empirical validity of Cogmed in terms of the program's efficacy in the improvement of working memory and inhibition, as well as the implications of commercial video game play on EF development. Children were placed into one of three groups: training, active control, and passive control. Children in the training group played CogMed for a period of 5 weeks, playing games that trained visuo-spatial memory and inhibition. Children in the active control group played commercial video games over the same period, while children in the passive control group only participated in the assessment' pre- and post-test. The working memory tasks required children to remember the order and location of visual presented stimuli. The inhibition tasks included go/no-go paradigm, a stop-signal task, and a flanker task. In the go/no-go task children are presented a square matrix split into for equal sized squares. Children's accuracy in each game determined their overall progress. Children in the training group performed significantly better on a set of novel WM tasks at post-test, but did not show the same level of improvement for inhibition (Thorell et al., 2009). The findings indicated that some EF skills were more malleable to change when presented in a game format. Other studies of CogMed have also found that it can effectively improve typically developing children's working memory (Riccio & Gomes, 2013), and children who show atypically poor working memory (WM) spans (Holmes, Gathercole, & Dunning, 2009). Computer-based interventions for EF however often lack generalisability (i.e. improvements sustaining outside the laboratory environment), and longevity (Riccio & Gomez, 2013). Moreover, it appears that

---

[1] A boss battle is a fight between the player and a significant computer controller opponent. Boss' are typically larger and tougher to eliminate and are often encountered at the end of a level.

computer-based EF training often provides the most benefit to children who are low-achievers from the outset, over children who are already competent learners in the classroom (Diamond, Barnett, Thomas, & Munro, 2007). The challenge is to develop a tool that trains the cognitive skill of interest, and for the learning of that skill to sustain and be applied to every day contexts. Given that videogame and interface technology are moving toward a more physical form of computing, an important consideration in the assessment of EF is the contribution of the motor system to executive skills.

Considering the role of the body in the assessment of EF

Despite the oft paraphrased definition of EF as the skills that help guide, manage, and regulate thought in the service of novel problem solving *behaviours*, the latter process has received considerably less attention to its cognitive counterparts. Perhaps this is because of the rhetoric used to describe EF processes. The terms high-level and low-level cognition for example has created a false dichotomy whereby sensory processes are conceptualised separately to the decision-making processes they inform (e.g. reasoning). One avenue that has somewhat attempted to smooth over this conceptual fractionation is research of the motor component of EF. Studies of the cerebellum's contribution to EF substantiates a holistic interpretation, where low-level processes like balance and timing are integral to the channelling of incoming information and response generation.

EF and the cerebellum

From a neuropsychological perspective, the cerebellum is proposed to be the control centre for the timing and execution of controlled movement. Lesions or trauma to this region results in postural, movement, and balance difficulties. Individuals with cerebellar lesions for example find it difficult to guess the time it takes for a ball to reach the floor once dropped from certain height. Because of the ideological convergence between cerebellum and cognitive function, namely, that the control of movement is inextricably tied to the cognitive processes responsible for movement generation (e.g. planning) researchers have integrated the cerebellum into models of information processing (Bloedel & Bracha, 1996). Originally considered solely as a source of input to motor control, the cerebellum has more recently been conceptualised as part of a network that feeds sensorimotor information to various cortical regions, including those responsible for EF; the prefrontal and frontal cortex (Strick, Dum, & Fiez, 2009). Further,

there is growing evidence demonstrating that the external behavioural manifestations of cerebellar damage are accompanied by impairment in inhibition (Brunamonti et al., 2014). Moreover, developmentally the cerebellum has a similar protracted maturation period to the pre-motor cortex, another region implicated in EF (Diamond, 2000). So, it is conceivable that EF ability is mediated by an individual's motor control. This a crucial point as presently, children's motor functioning has been an ad-hoc consideration in this domain: that poor behaviour is a consequence of impaired EF, not that they are part of the same system. Indeed, studies of children's motor coordination have shown that qualitative elements of early body movement can serve as an indicator of cognitive function. The development of fine and gross motor control for example articulates to aspects of EF.

Fine motor and gross motor control and children's EF

Fine motor control is characterised by small, precise movements generated by muscle, bone and nerves. A example of fine motor control is use of a keyboard, as each finger produces a small movement to depress a single button. Gross motor control on the other hand refers to larger movements involving the limbs. A good example of gross motor control is hopping, as movement engages the entire body to move, propelled by the legs. Each movement type is important as children's repertoire of movements develops their functional capacity in their environment. And, similarly to studies of cerebellar effects on cognition, the functional capacity offered by body movement extends beyond the behavioural component of action execution. Fine motor skills for instance correlate highly with EF ability at age 4 years (Cameron et al., 2012), as well as predicting rapidity of working memory processing between ages 5 to 11 years (Rigoli et al., 2013). So, the research in this domain shows that early fine motor control relates to children's executive processes. That is, the ability to produce small, controlled body movements, such as moving beads into a box and tracing the outline of a shape with a pencil are indicative of cognitive and behavioural control. However, the contrbution of fine motor control in this doamin is somewhat equivocal. Other authors have found both gross and fin motor control to associate with EF. When comparing a sample of children with intellectual disability – intellectual functioning characterised by imparied problem solving, reasoning and social skills (American Association on Intellectual and Developmental Disabilties (AAIDD), 2007) – and typically developing children's motor control and EF, Hartman, Houwen, Scherder, and Visscher (2010) found that intellectual function mediated locomotor

ability; tasks testing the ability to run, leap, gallop, jump and slide. Thus, children's intelligence predicted their gross motor coordination. A further investigation of the relationship between motor control and EF revealed that children who were less controlled in their execution of both fine and gross motor skills were also more likely to make impulsive decisions in the Towers of London. So, children's intelligence also plays a role in the relationship between EF and motor control. Furthermore, disorders characterised by fine and gross motor control difficulties, notably Developmental Coordination Disorder (DCD) show deficits in specific EF. Rahimi-Golkhandan, Steenbergen, Piek, Caeyenberghs, and Wilson (2016) asked 36 children – including 12 with DCD – aged 7 to 12 years to complete a modified version of the Go/no go task. In the task, children were presented a neutral face, that could be coupled with either a happy or a sad face, thereby providing an indication of the influence that affect has on children's EF. Happy and sad facial expression were included as 'go' and 'no go' trials respectively. Rahimi-Golkhandan et al. (2016) found that children with DCD were more prone to errors related to behavioural inhibition, commission errors: responding incorrectly to 'no-go' stimuli. Specifically, this group of children made more commission errors when responding to happy no-go faces, indicating that children with DCD have difficulties with hot EF (emotional as opposed to logical decision making; Zelazo, 2006). Hence, it appears there is support for both the development of fine and gross motor control in the development of EF. Some authors however, have found no such associations. Piek and colleagues (2004) investigated the relationship between motor ability and EF in a sample of children aged 6 to 15 years of age. Motor skill was assessed using a battery of assessments developed for the study of neuromuscular development, the McCarron Assessment of Neuromuscular Development (McCarron, 1997), which includes 5 fine motor and 5 gross motor skill tasks. EF was assessed using the Go/No-Go task, trail making/ memory updating task, and the goal neglect task. Correlations were then performed between the motor control battery and EF tasks to ascertain whether the two abilities were related. This analysis showed a relatively weak association between motor control and EF, instead showing that measures of attention correlate strongly.

So, the indication that the cerebellum, a cortical region classically defined as the cite responsible for movement control, is part of a network of cortical regions that regulate EF once again emphasise the importance of considering kinematic, physical process to the development and assessment of EF. Furthermore, examination of typically and atypically developing children's fine and gross motor control demonstrate the complex nature of this relationship. One thing that each of these investigations has in common is

that they correlate scores between separate motor control and EF tasks. By doing so, the authors limit the inferences that can be drawn between tests, as the cognitive and behavioural components of each could vary in such a way to support or hinder associations. One way to account for this potential variance would be to develop a task that at a cognitive level targeted a specific EF skill, that could be completed using either fine or gross motor control. The benefit of multimodal devices – like a floor mat – is that they offer the opportunity to assess children's gross motor control by engaging their whole body in an activity.

Experiment rationale

The focus of this thesis is to examine the nature of children's cognition with consideration of their environment and development. As this environment is one populated with various form of digital technology I have explained the potential influences of video games, and multimodal interaction on these processes. Additionally, multimodal interaction was examined by combining and comparing the use of a conventional user interface and the floor mat. The reasons why children's thinking would benefit while using this device are framed from the theoretical position of embodied cognition. Furthermore, EF was chosen as the cognitive ability for investigation given its developmental significance, and relevance to motor coordination. Studies of the cerebellum and motor control link conceptually to embodied cognition theory, in that the body inextricably tied to cognitive processes. However, here it is important to reiterate the differences between embodied cognition theory and EF to highlight the aspects of children's performance that will be examined empirically. Embodied cognition theories advocate that cognition is an activity that involved the physical brain, the body, and the environment. Thus, studying thinking from an embodied interpretation requires consideration of the individual's prior experiences and the environment in which they are thinking (Wilson, 2002). Studying the effect of multimodal interaction therefore must consider whether the action generated by the user articulates to the user's prior experience. As a floor mat supports the act of stepping and jumping it is ideal for studying children's embodied cognition. These actions are common to children's daily activities, such as walking to school and jumping over puddles. Multimodal interaction with this device therefore will allow children to draw on experience of these actions. Moreover, by encouraging body movement the device will allow children to offload cognitive resources, such that the act of thinking is shared between the brain and the environment.

As shown by Martin and Schwartz (20005), offloading cognition is mediated by the congruency between the learning materials and the actions performed. So, care was taken to design experiments that facilitated movements that were contextually relevant to the task. The literature of EF indicated that an additional feature of movement worth consideration alongside contextual relevance is the system it engages: fine or gross motor control. The evidence base in this domain is equivocal, however, there is the indication that both small and large body movements relate to EF competency. By bringing together the considerations of movement context and quantity, I predict that children will perform better on a task when the response action is both contextually relevant and engages the gross motor system. A finding of this nature would support three key assumptions outlined hitherto:

- Cognition is embodied.
- Executive functioning is inextricably tied to motor control.
- New technologies facilitate the above, and therefore improve children's cognitive processes.

To investigate each of these points children's embodied cognition and executive function were assessed using two specially designed planning and inhibition tasks that could be completed using a floor mat and a keyboard.

CHAPTER 3 – EXPERIMENT 1

As I have explained in the previous chapters, this thesis examined the relationship between action congruency, and EF. To do so, I worked closely with computer scientists story boarding and testing a task to ensure that it aligned with other experiments used in the EF literature. Another part development phase was to create a game that was suitable for children in the target age group, and choose a suitable mode of interaction that could be considered embodied. The resultant game 'Slippy's Adventure' is founded by research of EF. To begin this chapter, I first examined the developmental literature of children's planning, how it has been tested, and then describe how the principles of planning inspired my task: Slippy's Adventure. I finish this chapter by detailing the first empirical study conducted with the game.

Taking planning assessment forward

The Towers of London task provided insights to the processes that underlie children's planning capabilities, and was used as a framework to develop my own planning task. However, as I have argued in the previous chapters, the modification or simplification of classic neuropsychological tests is perhaps not the best way to assess children's cognitive capabilities. So, instead of creating a task that closely resembled the Towers tasks, I decided to create something new that had the appearance of a videogame, but retained the cognitive principles of a Towers task. First, I will explain how I developed my planning task, to highlight how the cognitive principles of planning have been maintained.

To select a format for the task that children would find engaging, I first investigated the media that was available to children online. I visited various children's games websites including CBeebies games (http://www.bbc.co.uk/cbeebies/games) and other children's puzzle game webpages (e.g. http://www.gamingdelight.com). What became clear was that many online games designed for children did not merit an EF component. Many of the CBeebies games for example include educational content, supplemented with simple point-and-click games, or reward based puzzles. While these types of games are appropriate in other domains, for my experiment I decided to specifically for games that contained an element of planning.

I eventually found a suitable candidate by the name Kaeru Jump (http://www.gamedesign.jp/flash/kaeru/kaeru.html). Kaeru Jump is a Flash game (an internet based computer game) in which the player assumes the role of a frog who is situated in a lily pond. In the pond, there is an array of stones. The goal of the game is to direct the frog to each of the stones while abiding to a set of rules. They are as follows:

- The frog can only move in four directions on the screen (up, down, left, and right)
- It cannot jump diagonally
- It cannot jump backwards
- A stone will disappear once it has jumped from
- The frog must land on all the stones shown in the pond
- The frog cannot jump in the water

After having played the game I revisited the core principles of planning as stated in the literature:

- Breaking down a problem into its constituent operators
- Formulating a sequence
- Initiating actions that followed the sequence
- Recognising when an error had been made
- Modifying the plan per these observations

Several elements of the game fitted the literature of planning in psychology, while presenting the task in a modern and child appropriate manner. Planning was essential prior to taking the first move. If I did not take a deliberated, careful approach to the levels in Kaeru Jump, I often found myself either stuck or hacking away at the problem. This was primarily due to the games rules concerning the frog's movement. The inability to jump diagonally meant that the problem could be broken down into a series of movements made in four possible directions (i.e. orthogonally). Because the rocks disappeared after having been jumped from, the strategy that the player formulated had to update per the remaining rock configuration after each move. Restrictions on the frog's movement backwards meant that the player had to be careful so as not to land on a rock that would leave the frog facing toward open water with no surrounding rock.

Success in Kaeru Jump required a high-level problem searching (e.g. 8-moves), and in doing so, also required proficient working memory and inhibition (Sweller, 1988). It involved planning as formulating a strategy was necessary to identify the route across the

rocks that would include all the rocks. Working memory was required insofar that the rules of the game had to be kept in mind for each planned move, and to update the route considering the new position of the frog after each jump. Inhibition was required, in that the problem solver had to refrain from making snap decisions, particularly for the very first move in the game, as this could lead to failure in the resulting route taken.

Kaeru Jump therefore aligned well with the cognitive skills required for planning, and other aspects of EF. However, I considered the game inappropriate for assessment with children in its original format. This was due to several reasons, such as the lack of control I had over the configuration of each level (this was randomised), the search depth was too high, and the layout of the game did not provide the sense of embodiment I wanted to achieve. So, working closely with colleagues in computer science, I storyboarded and created a new planning task drawing inspiration from both the literature of EF and Kaeru jump to create Slippy's Adventure.

Slippy's Adventure

In Slippy's adventure children assume the role of a virtual frog, Slippy, whose goal was to collect treasure. To do so, children navigate Slippy to the treasures location, a golden lily pad. Children were also told that there were certain rules they would have to follow to successfully navigate to the golden lily pad:

- Slippy cannot jump diagonally, only forwards, backwards[2], left, and right
- Slippy cannot jump in the water
- Slippy can only jump onto other lily pads
- The goal of the game is to reach to golden lily pad in as few hops possible; the number shown in the top left hand corner of the screen
- After jumping from a lily pad, it will disappear, so you can only land on a lily pad once

So, Slippy's adventure was similar in several ways to the design of Kaeru Jump with modifications applied to give me more control of the tasks demands, and create a task more appropriate for the target age group.

---

[2] The terms 'forwards' and 'backwards' were used instead of 'up' and 'down' as the frog was programmed to face forward for the duration of the task, to match the perspective of the participant creating a greater sense of embodiment.

Taking the mind's eye of the virtual character

Slippy only ever faced forward while resting on a lily pad so that the perspective of the frog mirrored that of the participant. Papert's (1980) work with Logo, a programming language for children made accessible with a turtle avatar inspired this decision. In Logo, children inputted geometric instructions to a physical or computer generated turtle to match the geometry of a line drawing. By doing so, children were forced to consider the perspective of the turtle, thereby improving their understanding of the problem space (Stager, 2016). Thus, I hoped that children would find the task more embodied in the sense that the perspective they took during the completion of the task matched that of the frog.

Trial composition

Also, I created a set of trials that allowed children to complete the task using different routes, whereas Kaeru Jump had a single route. This measure was taken to spare children the frustration of becoming stuck on each trial if they failed to identify the optimum route. In Kaeru Jump, each level was taken randomly from a library of lily pad configurations. As such, the order of trials was not progressive, potentially beginning with more complex trials (e.g. optimum number of moves = 7). To adopt a formalised experimental approach to trial creation, I applied the structural parameters of the Towers of London as identified by Kaller et al. (2004) [3] to the trials in Slippy's Adventure:

1) Minimum/optimal number of moves (henceforth optimal number of moves). Tower configurations that require more moves to completion are conceived to be more difficult, as the problem solver much search a larger problem space to determine the optimal outcome (Newell & Simon, 1972). The optimal number of moves in Slippy's adventure

---

[3] The other Towers of London structural parameters identified by Kaller et al., (2004) 'Goal hierarchy' and 'Patterns of subgoaling' were not considered at these parameters did articulate explicitly to the layout of Slippy's Adventure (e.g. some of the moves executed by children could be considered both optimally and sub-optimally).

was presented in the top left-hand corner of the screen as a fraction: each move executed was counted on the numerator, the denominator presented the optimal number of moves.

2) Number of possible optimal solutions: This was set to 1.

3) Number of suboptimal solutions: The was set to 1, although on some trials it was possible for children to backtrack, adding additional moves to the suboptimal route.
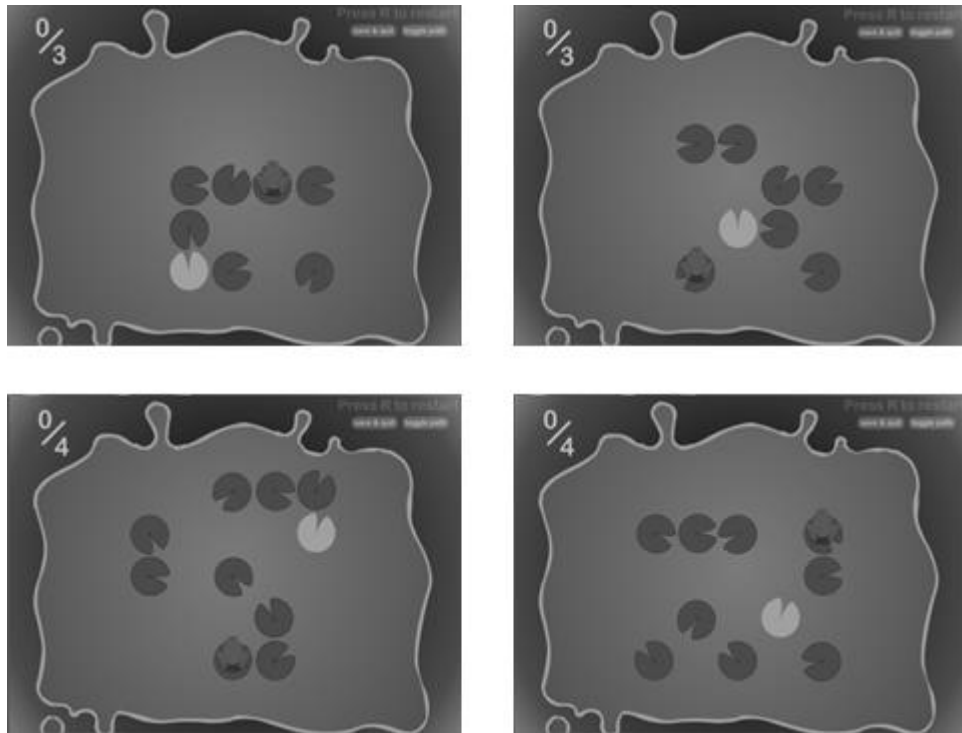
Figure 1. Trials in Slippy's Adventure: the top two images are 3 move trials; the bottom two images are 4 move trials.

Figure 1 shows the presentation of Slippy's Adventure. The frog is situated on the starting lily pad. The task is to navigate the frog to the golden lily pad in the number of moves shown in the top left hand corner of the screen. Children were introduced to the task through a series of practice trials that did not test planning, but instead, familiarised them with the tasks layout. It was evident from these practice trials that children found the game engaging, and understood the requirements of the task. The configurations in figure 1 were generated using a 5×5 grid, onto which operators (green lily pads), the starting position (where the frog began), and the goal-state (the golden lily pad) were specified. The top two images in figure 1 are 3-move trials, and the bottom 4 move trials.

In each trial, operators were entered by doubling the number of optimal moves (e.g. in a 3-move trial, there were six lily pads entered onto the grid). Following this logic created a task that could be completed in three ways: 1) taking the optimal route; 2) taking the suboptimal route; 3) getting stuck. Taking the optimal route involved completing the task in the number of moves as shown in the top left hand corner of the screen. Sub-optimal completions would take place if the child chose a route that included several moves above the optimal number. Children could get stuck on the task if they chose a route that would leave finish with them on a lily pad, without an accessible operator nearby. If children tried to jump in the water with the frog, the program logged the move as an 'invalid move'.
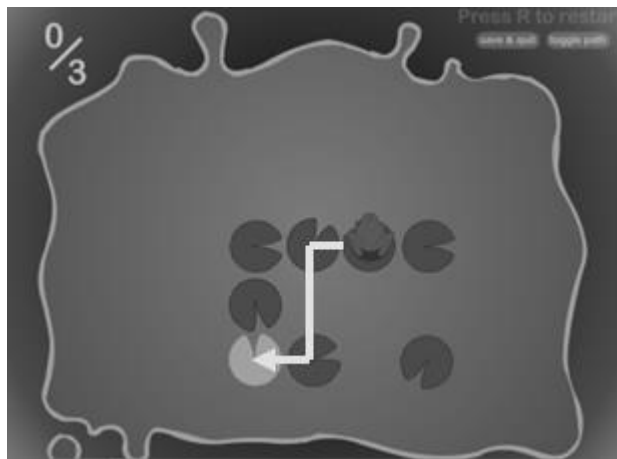
Figure 2. Arrow shows the optimal completion of 3 move level.

Figure 3. Arrow shows the sub optimal completion of 3 move trial in Sippy's Adventure, taking four moves.

45

Embodiment and planning

As stated, previous work in the domain of embodiment and user interfaces assessed participant's performance between two different modalities. Chao et al. (2013) examined the differences in the retention of action phrases after those phrases had been re-enacted using either a keyboard or a Kinect. Indeed, adult's memory for these phrases was better a week later if they had encoded the phrases by acting it out using a Kinect. The findings indicate therefore that when an action is embodied, the information that is presented during the time of embodiment is processed more effectively; in the above example, by improving short-term memory. Similarly, this experiment also included two interfaces: a PC keyboard and a floor mat. The PC keyboard contains directional buttons situated in a cluster, arranged in a logical manner. Computing education at Scottish primary level (approximately ages 5-11 years) requires pupils to use computer keyboards (Education Scotland, n.d.), so, I did not expect this device to be overly challenging or unfamiliar to children. The keyboard was considered the 'less embodied' interface, as the actions necessitated by the device did not offer the same level of physical interaction, or movement similarity to the floor mat. In contrast, the floor mat afforded a degree of embodiment as children could jump between a set of directional squares, jumping like the virtual frog, thereby affording them the opportunity to execute congruous actions, and to share cognitive resources between their brain and body. With respect to planning, research has shown that age is a significant factor in children's initial thinking time and number of moves (Kaller et al., 2008; Unterrainer et al., 2015), and the number of rule violations (Wong, Maybery, Bishop, Maley, & Hallmayer, 2006). Here, I also considered a few other dependent variables of interest: trial completion time and the likelihood of achieving an optimal completion on the first turn. These dependent measures were added to ascertain the factors that lead to successful planning from temporal and problem solving dimensions. As planning is being measured by a variety of dependent variables it is important to comment on what 'better planning' constitutes.

Experiment dependent variables as indicators of good planning

Initial thinking (sec)

With regards to initial thinking time there is little consensus whether efficient planning is a consequence of longer or shorter planning time. However, given the novelty

and motor component to the present paradigm I predicted that longer initial thinking times would be associated with better planning performance (i.e. fewer moves to completion).

Item completion time (sec)

I expected shorter item completion times to be associated with better planning, as this would reflect children's identification and utilisation of the optimal strategy.

Number of moves

Better planning would be indicated by fewer moves to completion.

First attempt success

The more frequent children's first attempt success (i.e. completing the item in the minimum number of moves on the first turn) the more efficient their planning.

Number of invalid moves

The fewer invalid moves executed the better the planning.

Together, the task assessed the relationship between embodied cognition, planning, and age. As embodied cognition theorists advocate that contextually relevant body movements (e.g. those that relate to the real-world action) and offloading cognitive resources enhance the cognisors information processing, here I expected children to be better planners while using the floor mat. I expect there to be age specific effects of embodiment, as children in the older group have more sensorimotoric experiences to draw upon to their younger counterparts. Children aged 7 should show better planning performance on the floor mat compared to children aged 5.

METHOD

Participants

Twenty-six typically developing children took part in the experiment, including 13 from year one, known as primary (P1) in Scotland (M = 5.05, SD = 0.26), and 13 from primary three (henceforth P3) (M = 7.54, SD = 0.24). Half of the participants were female. Participants were recruited via letters sent to parents detailing the aims of the investigation. Parents provided written consent, and verbal assent was given by participants. The study was approved by Heriot-Watt University's Ethics committee, approval number: 2103:2.

Materials

Slippy's Adventure was played on a Dell Precision M4800 laptop, with a 1920 x 1080 display. In the less embodied keyboard condition, participants sat at a desk and used the directional buttons to complete the planning task. In the embodied condition, a Konami Dance mat was plugged into the laptop via USB. An emulator, Joystick-to-keyboard (J2K, http://emulation-evolved.net/), was used to interface the floor mat with the laptop, so each directional button mapped onto the analogous keyboard key.

Design

The study was a 2 × 2 × 2 mixed design with a within subject's factor of modality (Floor mat, keyboard), Optimal number of moves (3-move, 4-move) and a between subject's factor of age group (P1, P3). Six dependent variables were included in the analysis: Initial thinking time (sec): The time between trial onset and the first move executed; Trial completion time (sec): The time taken to successfully reach the end of the trial; Number of moves per trial: The number of moves taken to complete a trial; Move efficiency: A calculation based on the number of moves children completed divided by the optimal number of moves. Move efficiency was thus a standardisation of a child's move count across 3-move and 4-move trials; Likelihood of first time optimal completion: A probability generated based on the success of each trials first attempt. If a child completed a trial in the optimal number of moves on the first attempt this outcome was coded as 1, otherwise responses were coded as 0; Number of invalid moves: The

number of occasions children attempted to jump to a location the frog could not navigate to. This included inaccessible lily pads and the surrounding water.

Procedure

Participants completed the task at two separate sessions, 2 weeks apart; one session using the keyboard, and the other using the floor mat. The presentation order of modality (keyboard, floor mat) was counterbalanced. At the first session participants completed a block of 10 practice levels before testing. This practice block did not require planning, but instead contained a set of levels designed to familiarise children with the task, and the use of each modality. The test block included 20 trials; ten 3-move problems and ten 4-move problems. The order of trials within each block was randomised. In total, children completed 40 test trials across two sessions. To begin, I carefully explained the tasks instructions making sure that children were sure of what was expected of them. The instructions gave context to the experiment, as were told that they were going to play a game where they had to help a frog called Slippy collect treasure, and outlined the rules of the task. Children were told that Slippy could only jump from one lily pad to another, that he could only jump forwards, backwards, left, and right, that he could not jump in the water, and that he could only jump onto other lily pads. Finally, children's attention was drawn to the top left hand corner of the screen where a jump counter was displayed. I finished by explaining that the number shown in the move counter was the number of moves that the child should try to complete the puzzle in.

RESULTS

Thesis data modelling

All data analysis for the experiments detailed in this thesis were completed using R Statistics software (R Core Team, 2016). The plyr package (Wickham, 2011) was used to pre-process the data, the ggplot2 package (Wickham, 2009) was used to generate graphics, and the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) was used for analysis. Interval dependent variables (e.g. participant's response time (RT), initial thinking time, and total completion time) were analysed using linear mixed effects modelling (LMEM). Dependent variables that generated binomial data (e.g. accuracy and first time optimal completion) were analysed using mixed effects logistic regression. Mixed effects modelling was selected for analysis to provide a more accurate interpretation of the data, and to demonstrate the utility of this analysis in developmental research.

Mixed-effects models

In mixed-effects models, both fixed and random effects are considered in the modelling process to determine the best fitting model structure given the variance in the data. Fixed effects are the parameters that are known hold a specific relationship a priori (Crawley, 2013). In this experiment, optimal number of moves is a fixed effect a set of trials will require more moves to completion than others. Random effects are elements of a predictor variable that are randomly sampled from a potentially infinite number of factor levels. The sampling of participants in psychological research for example, can be considered a random effect. Even in studies with targeted sampling techniques – such as selecting children of a specific age – the sample is drawn from a larger population (e.g. every child in the UK of that age). In the following experiments, random variance by sample, item, and interface was considered in each model's composition. That is, the potential variance attributable to sampling, participant's response to an individual trial, and modality preference was included in the modelling process.

Accuracy of interpretation

LEM was chosen for analysis to provide a more precise measure of RT relative to the group mean (Lo & Andrews, 2015). Fixed effects consider the systematic variance between parameters by estimating and comparing their values. Random effects on the other hand estimate the degree that mean responses change for each unit in the random

factor (e.g. each participant). Modelling both fixed and random effects therefore allows the experimenter to model the extent that variance in the model is explained by a prediction, or hypothesis variable, over and above the random sampling variance. So, responses are measured more accurately than with a reduced probability of artificially inflating the variance attributed to a fixed effect (e.g. a Type I error). Defining the random effects structure of each model involves the identification of the data's structural dependencies; pivotal features of the data's variance that include a level of 'randomness'. Structural dependencies can be identified by examining meaningful clusters in the data (e.g. there may be a trial that causes an elevation in participants RT), cross-classification, nesting, blocking, and counter balancing.

Modelling process

The same protocol for model composition was followed for each analysis. First, the random effect of participant was considered alongside the fixed effects and the models intercept case. So, each analysis with mixed effects used the following model structure as the baseline:

[4]`Model = y ~ 1 + b + (1|Participant)`

In the above model, *y* is the dependent variable of interest, *1* represents the intercept term, *b* is the predictor variable (of which there can be several, e.g. b_1, b_2, b_3 ...etc.) and the random effect of participant is denoted by `(1|Participant)`. This model was then built upon by entering each random effect in a stepwise manner, and testing the contribution of the random effect by conducting an analysis of variance (ANOVA) between the baseline model and the new model. If this ANOVA between models produced a significant effect, random effect was added to the model. The same process was then applied for each of the fixed effects followed by the hypothesis variables. This stepwise process ensured that the model accounted for as much variance present in the data, before entering the hypothesis variables.

---

[4] Models in this thesis are presented in `Courier New` font to demonstrate how a model is composed in R Statistics, to provide a reference for researchers interested in conducting LMEM in R.

The effect of Item (denoted by `(1|Item)`) was selected given that each level (e.g. experiment *item*) in the task was different in composition, and randomly generated in a grid. In experiment 1, this grid was 5×5, and in experiment 2, the grid size was expanded to 10×10 (see Chapter 4 for more details of experiment 2). Hence, there was a lot of scope in terms of each items composition, and this composition could have affected children's performance in a random manner. For instance, certain configurations may have been easier for some children to process, as they may resemble puzzles they have encountered prior to taking part in the experiment. Modality was considered as a random effect (denoted by `(1|Modality)`) as some children might have randomly performed better on this device over the keyboard by their preference for gross motor movement over fine motor control.

In experiment 3, an additional random effect of item direction was considered, as the target stimulus could point either left or right. So, there was potential random variance because the child's preferred direction of response. (more details about this experiment, and the random effects structure adopted in the modelling process are detailed in chapter 5).

Step1: Random effects modelling	Step 2: Fixed effects modelling	Step 3: Hypothesis modelling
1) Add random effect of participant to baseline model	1) Add cognitive assessments subtest and total scores independently to model	1) Add each hypothesis variable as a fixed effect
2) Add random effect of Item	2) Test contrubution to models variance via ANOVA	2) Test hypothesis varaibles contrubution to model via ANOVA
3) Add random effect of Modality	2) Retain fixed effects that contribute significantly to models variance	3) Retain hypothesis variables identified as significant by ANOVA
4) Retain random effects identified as significant contributors from between-model ANOVA		

Figure 4. Linear-Mixed effect modelling process adopted in thesis.

Note that in each description of the modelling process I do not detail the random effect modelling. Rather, I speak about the modelling with the fixed effects and hypothesis variables, as these effects are of theoretical importance. The term 'modality' refers to the different devices used for response generation (Floor mat, keyboard or numberpad). Item refers to a specific trial.

Fixed effects structure

In experiment 2 and 3 cognitive assessments were administered to the children to investigate if children's EF, intelligence, and motor coordination played a significant role in their task performance. Each of these assessments included several subtests, some of which could be argued to relate strongly to the requirements of the experimental task. However, for ease of interpretation, I have not included the modelling of every assessments subtest, but focus on the subtests that significantly contribute to the variance in the model. So, although the modelling process outlined in experiments 2 and 3 do not cover all the subtests contributions to the model's variance in the modelling description the effect of each of these subtests has been tested.

Table 1

T-value adjustments for each experiment.

Experiment	N	t-value	p
1	26	2.08	< 0.05
		2.86	< 0.01
		3.81	< 0.001
2	20	2.09	< 0.05
		2.91	< 0.01
		3.92	< 0.001
3	30	2.07	< 0.05
		2.84	< 0.01
		3.76	< 0.001

Given that there were a different number of participants available for each experiment I also adjusted the t-values given the degrees of freedom. Table 1 above provides an index for each experiment's t-values and their respective value for *p* given the number of participants (N). In the following experiment, a t-value of 2.08 indicated that the parameter of interest contributed to the variance in the model to the probability of $p < 0.05$.

Hypothesis variables structure

Whether a hypothesis variables entered each model depended on the hypothetical construct of interest and practicalities of the research design. As the research focussed on the effect of embodied cognition on children's task performance, each hypothesis variable related to task completion and modality. Consideration of the research design however constrained some aspect of data analysis. For example, I expected that children's initial thinking time (sec) and item completion time (sec) would be elevated in this respect, by the type of the gross motor skills necessary to use the mat, in contrast to the fine motor skill required to use the keyboard.

So, when modelling initial thinking time and item completion time in experiment 1 and 2 the hypothesis variables included two interactions: Modality × Optimal number of moves, and Modality × Group, rather than a fixed effect of Modality. An interaction between Modality × Optimal number of moves was considered as it would demonstrate the beneficial effect of embodied cognition on children's initial thinking time between each of the two levels of optimal number of moves. In other words, the interaction would signify that children's initial thinking time on 3-move and 4-move trials while using the floor mat was closer to their initial thinking time relative to completing trials using the keyboard. The interaction between Modality and Group was also considered as this would demonstrate that the older children were better planners using the floor mat.

However, for other dependent variables measuring the frequency of an event (e.g. number of moves), Modality was entered as a hypothesis variable, as well as the hypothesis variables stated above.

EXPERIMENT 1 ANALYSIS

Initial thinking time distribution

   To begin the analysis, I first explored the distribution of initial thinking time. Figure 5 below is a histogram of the initial thinking time data distribution. An outlier case was removed as one child stopped for a break at the beginning of a trial block (initial thinking time = 2799.25). Exploration of the data also revealed that 2 participants (P04, P08) data for the keyboard trials was missing (3.8%). Adjustments to the descriptive and inferential statistics were made to account for this loss of data.
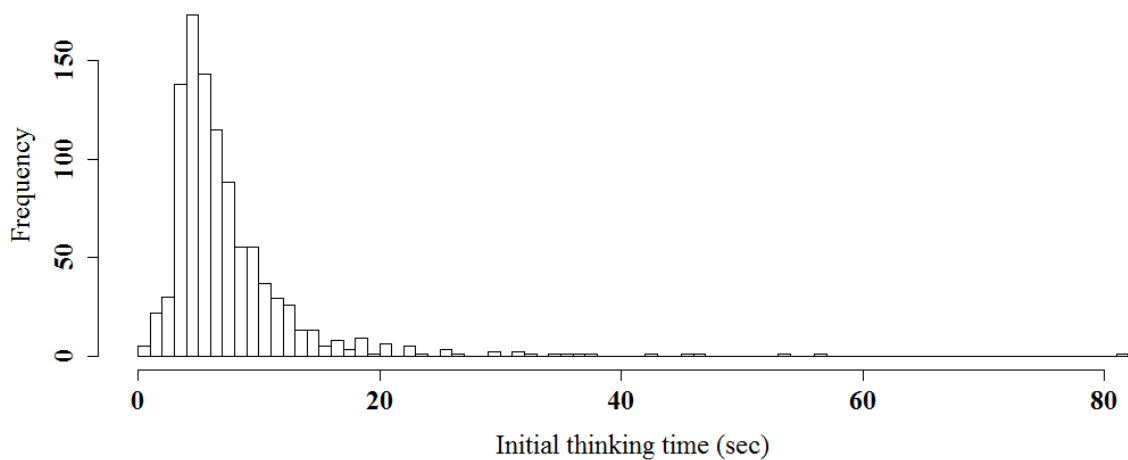
Figure 5. Histogram of initial thinking time (sec) for first move made prior to 100sec.

   From my examination of this distribution 25 observations fell between 20sec and 100sec. As children were encouraged to think carefully about their choice of move, I did not remove cases based on their deviation from the mean, e.g. the three-sigma rule. Long initial thinking times - up to 100 secs – related to children's careful planning, rather than anomalous data.
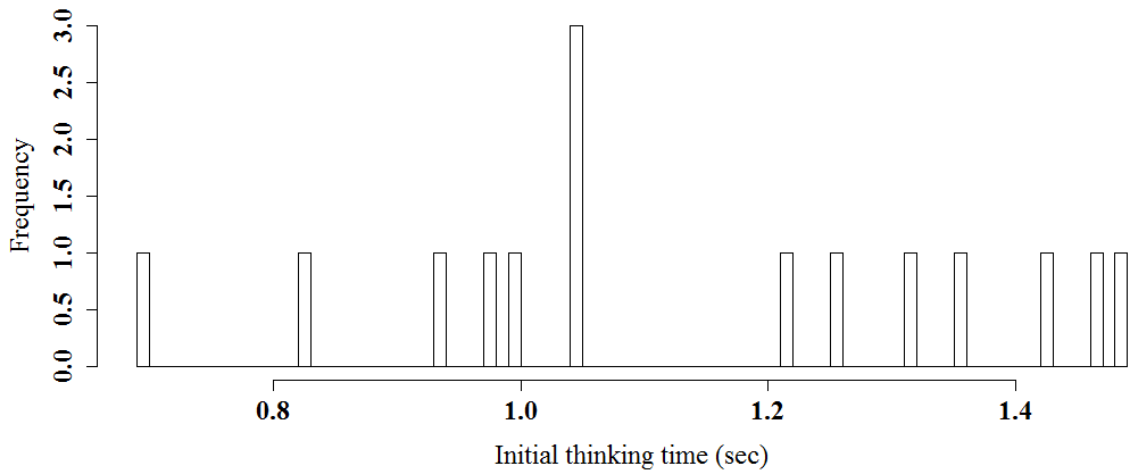
Figure 6. Histogram initial thinking time less than 1.5 seconds.

Moreover, my examination revealed that five observations fell below 1 second, all of which took place on the floor mat. After closer inspection of these a single case was removed where Initial thinking time = 0.690 seconds, as this time related to problems with position of the feet, rather than planning. The child who produced this time accidentally had one foot on a directional square at the beginning of a trial. So, the final distribution of initial thinking time had a range of 0.7:100 seconds. To model this data, and retain observations where children spent a long time planning their move, a log transformation was performed on this dataset. Figure 7 shows the log of this distribution.
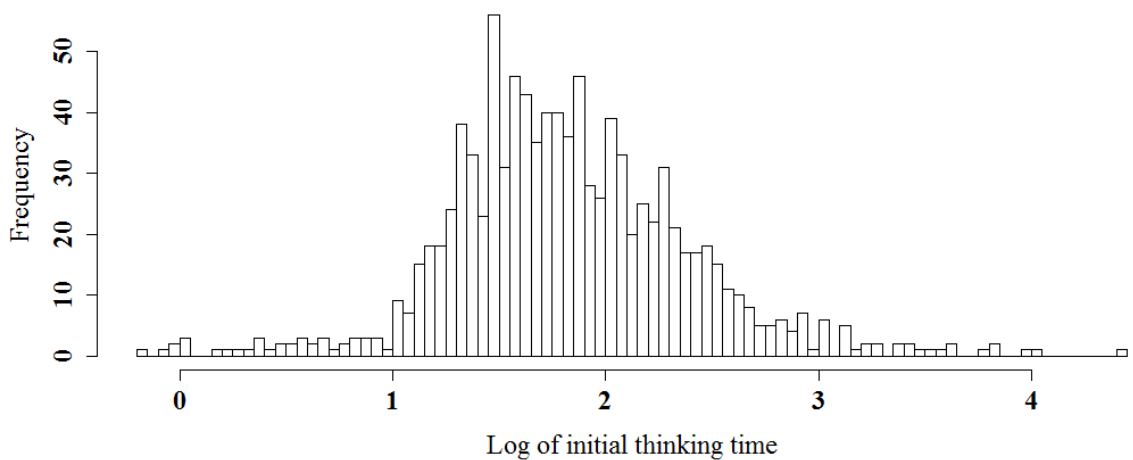
Figure 7. Log of initial thinking time between 0.7:100 seconds.

Taking the log of the initial thinking time distribution produced a more model-able Gaussian curve. So, the analysis reported below are taken from the log of initial thinking time.

Initial thinking time descriptive statistics

Descriptives pertaining to the final distribution are given in the table below. Given the non-parametric, positively skewed, distribution of the initial thinking time data, here I report the median and range from children's first attempt. The percentage of children who completed the first level in the optimal number of moves is also provided to give an indication of the effect of each hypothesis variable on children's planning performance.

Table 2

Children's Initial Thinking Time (sec) and First Attempt Trial Completion (%).

	Min	Max	Median	First attempt
Year Group				
P1	1.00	56.97	6.50	20.77%
P3	0.83	81.77	5.45	33.96%
Optimal number of moves				
3-move	0.98	81.77	6.20	32.92%
4-move	0.83	42.99	5.56	23.54%
Modality				
Floor mat	0.83	56.97	5.66	24.62%
Keyboard	2.19	81.77	6.16	29.79%

Initial thinking time

To begin the analysis, Linear mixed effects modelling was used to model the effects of the hypothesis variables, and fixed and random effects on children's initial thinking time. Fixed effects included Group (5 years, 7 years) and Optimal number of moves (3-move, 4-move). Age group was considered a fixed effect given the recent finding that older children take less time to plan, and that the level of optimal number of moves also mediates children's initial thinking time.

To begin the modelling process, I entered the fixed effects of Group and Optimal number of moves, and the random effect of Participant. I then investigated the random effects Item and Modality. Investigation of the random effects structure revealed that both Item and Modality contributed significantly to the unexplained variance in the model (both $p < 0.001$). These results produced the following baseline model:

```
Model (1) = log(Initial thinking time) ~ 1 + Group +
Optimal number of moves + (1|Participant) + (1|Trial)
+ (1|Modality)
```

I then moved on to entering each hypothesis variable into the model. To begin, I added the interaction between Group and Modality, denoted by Modality*Group. All interactions documented in this thesis follow this notation.

```
Model (2) = log(Initial thinking time) ~ 1 + Group +
Optimal   number   of   moves   +   Modality*Group   +
(1|Participant) + (1|Item) + (1|Modality)
```

An ANOVA between model 1 and model 2 yielded a significant effect ($p < 0.05$) This hypothesis variable was added to the model. In the next model, I added the hypothesis variable: Modality $\times$ Optimal number of moves interaction.

```
Model (3) = log(Initial thinking time) ~ 1 + Group +
Optimal   number   of   moves   +   Modality*Group   +
Modality*Optimal   number   of   moves   +   (1|Item)   +
(1|Modality)
```

A comparison of model 2 and model 3 with an ANOVA yielded a, non-significant effect, $p = 0.62$. Therefore, the modality children used to complete the game did not have a significant impact on their initial thinking time between 3-move and 4-move problems. So, Modality × Search was dropped from the model. The following summary relates to a regression performed on model 2.

Table 3

Best predictor model of children's initial thinking time.

	β	Predicted ITT	SE β	t-value
Intercept	2.21	9.12	0.18	9.67***
P3	-0.06	0.94	0.02	-1.00
3-move	-0.09	0.92	0.05	-1.77
Keyboard	0.26	1.30	0.08	3.73**
P3 * Keyboard	-0.06	0.94	0.04	-1.88

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Predicted ITT = Predicted Initial Thinking Time.

P1 * Keyboard = Children in P1 using the keyboard.

Table 4

Random effect structure for children's initial thinking time.

	Variance	SD	p
Participant	0.07	0.27	N/A
Item	0.01	0.09	0.000***
Modality	0.00	0.00	0.000***
Residual	0.22	0.47	N/A

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

In table 3 predicted values were estimated by calculating the exponent of the regression estimate (i.e. β). This process is repeated for each of the following analyses, to provide an indication of each parameters effect on children's performance out of the log space. Linear mixed effects revealed that Modality also explained a significant portion of variance in the data, whereby participants took significantly longer to plan their first move using the keyboard compared to the dance mat, $t = 3.373$, $p < 0.01$. No other effects were significant.

Item completion time

In this section I investigated the effect of each of the hypothesis variables on participant's completion time per trial. This included trials that were completed in the optimal and sub-optimal number of moves. First, I generated a histogram to examine the distribution of this data.
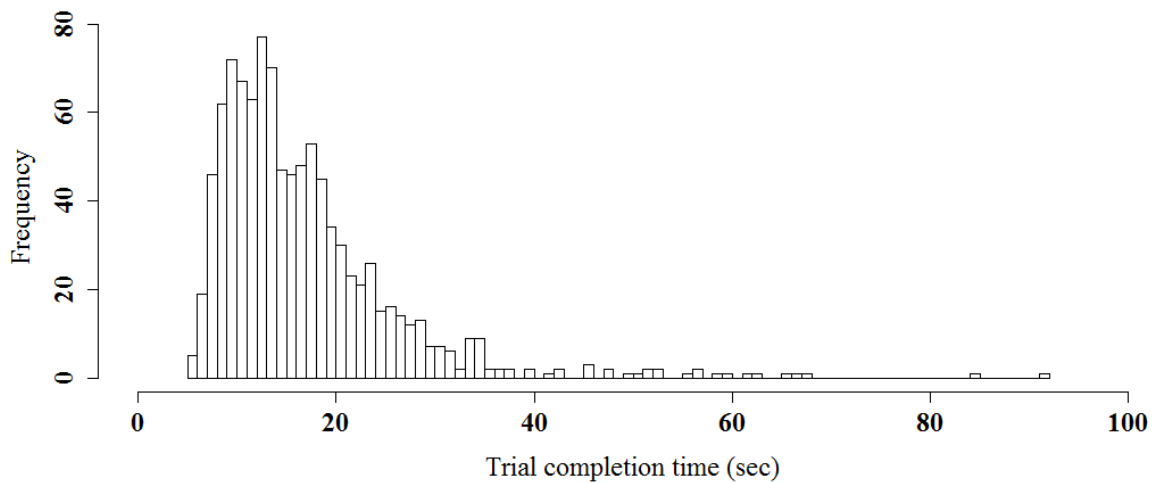
Figure 8. Histogram of total time to completion (sec).

A log transformation was then performed on the completion data to provide a more model-able, Gaussian like distribution for analysis (see Figure 9).
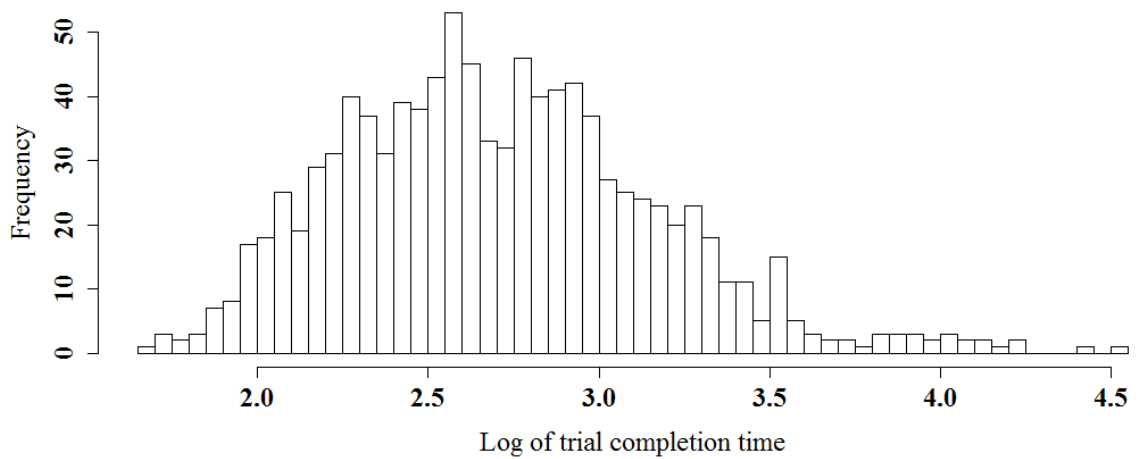
Figure 9. Histogram of the log of completion time.

Completion time descriptive statistics

Given the non-parametric distribution of children's completion time, I report the Range and Medians for children time to complete a trial.

Table 5

Children's item completion time (sec).

	Min	Max	Median
Year Group			
P1	6.40	84.78	16.22
P3	5.40	91.33	12.95
Optimal number of moves			
Three-move	5.40	91.33	13.42
Four-move	5.53	84.78	15.07
Modality			
Floor mat	6.15	84.78	15.26
Keyboard	5.40	91.33	13.63

Relationship between initial thinking time and completion time

It is conceivable that the longer children spent planning the less time it would take for them to complete each trial. Figure 10 is a scatter plot investigating the relationship between these two outcome variables:
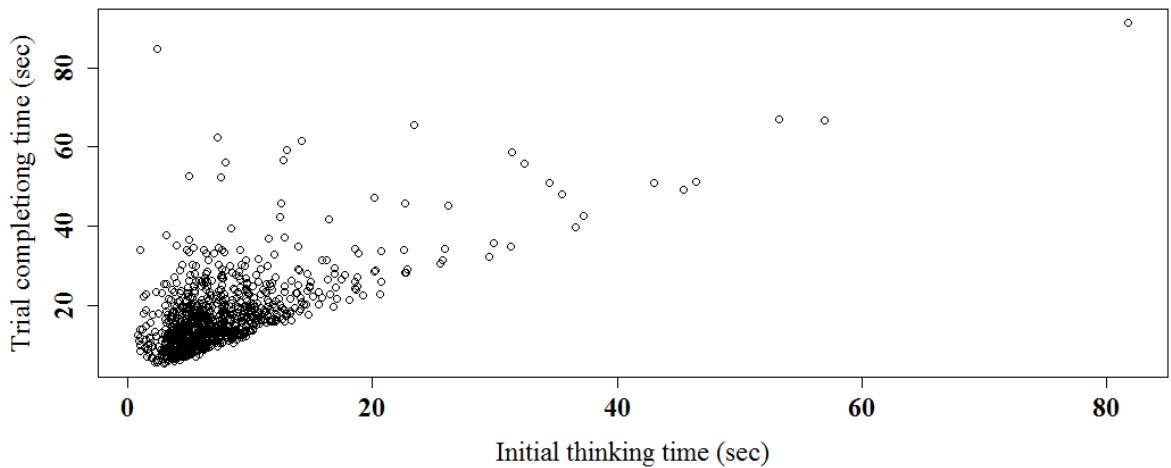
Figure 10. Scatter plot of completion time and initial thinking time, both provided in seconds.

These two variables had a moderate correlation, $r = 0.54$. So, rather than indicate a negative correlation, the scatter plot demonstrates that longer initial thinking time corresponded to longer completion time.

Mixed-effects modelling of item completion time

Linear mixed effects modelling was used to model the effects of the hypothesis variables, and fixed and random effects on children's completion time. Fixed effects for this analysis included Group (5 years, 7 years) and Optimal number of moves (3-move, 4-move). Two factors were considered as random effects: Item and Modality. The hypothesis variables were the same: Modality × Optimal number of moves, and Modality × Group. So, the modelling process followed the same protocol as for initial thinking time.

Investigation of random variance in the model detected significant random variance because the experimental Item ($p < 0.001$) and Modality ($p < 0.05$). These analyses produced the following baseline model:

```
Model (1) = log(Completion time) ~ 1 + Group + Optimal
number  of  moves  +  (1|Participant)  +  (1|Item)  +
(1|Modality)
```

First, I added the hypothesis variable of Modality × Group.

```
Model (2) = log(Completion time) ~ 1 + Group + Optimal
number of moves + Modality*Group + (1|Participant) +
(1|Item) + (1|Modality)
```

An ANOVA between model 1 and model 2 yielded a near significant effect ($p = 0.053$). So, the interaction Modality × Group was excluded from the model. In the next model, I added the interaction between Modality × Optimal number of moves.

```
Model (3) = log(Completion time) ~ 1 + Group + Optimal
number of moves + Modality*Optimal number of moves +
(1|Participant) + (1|Item) + (1|Modality)
```

A comparison of model 2 and model 3 with an ANOVA yielded a non-significant effect ($p = 0.12$). So, Modality × Search was dropped from the model.

The regression results reported below therefore relate to model 1.

Table 6

Best predictor model for children's item completion time.

	β	Predicted TCT	SE β	t-value
Intercept	2.66	0.92	0.18	-14.71***
P3	-0.21	1.05	0.08	-2.54*
4-move	0.04	1.32	0.05	0.94

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Predicted TCT = Predicted Item completion time.

Table 7

Random effects structure of children's item completion time.

	Variance	SD	*p*
Participant	0.04	0.20	N/A
Item	0.01	0.09	0.00***
Modality	0.00	0.04	0.02*
Residual	0.19	0.43	N/A

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Linear mixed effects revealed that the fixed effect of Group explained a significant portion of the variance in the model. Children in P3 took on average 1.05s less to complete trials relative to children in P1, $t = -2.54$, $p < 0.05$. There were no other significant effects.

Number of moves analysis

  Next, I investigated the factors that contributed to the number of moves children made in the block of trials. This data set includes both optimal and sub-optimal completion strategies, as I wanted to capture variance pertaining to search strategy in the model, e.g. the more moves a child took to complete a trial, the less likely they were to demonstrate a means-ends analysis strategy. To do so, I consider two dependent variables: move efficiency; optimal completion on the first attempt. Move efficiency is a metric generated from the number of moves it took children to complete an item. Given that some items included three and four move puzzles, the number of moves was adjusted based (i.e. children took more moves to complete four move puzzles by experimental

design). Each move count was therefore divided by the optimal number of moves to generate a move efficiency score. For example, if a child took 9 moves to complete a 3-move item, their efficiency score for that trial would be 9/3 = 3. Hence, a score of 1 indicated that the child completed the trial in the optima number of moves.

If a child became stuck, the level was restarted, but the number of moves from their first attempt were added to their new move count.

Table 8

Children's mean move efficiency and frequency and percentage (%) of first attempt optimal completions.

	Move efficiency	First attempt optimal completion	Percent first attempt optimal completion
Year Group			
5 years	1.50	108	12.13%
7 years	1.33	163	19.52%
Optimal moves			
3-move	1.67	158	18.81%
4-move	1.25	163	19.52%
Modality			
Floor mat	1.50	128	14.71%
Keyboard	1.33	143	16.73%

Note. The closer Move efficiency is to 1, the fewer moves a child executed. First attempt optimal completions differ from the values reported in table 2, as those values represent optimal and sub-optimal completions on the first attempt.

Of interest was the effect of initial thinking time on children's first attempt optimal completions. It is feasible that on those occasions longer initial thinking times would increase the likelihood of completing an item on the first attempt in the optimal number

of moves as they would have more time to evaluate the problem and identify the correct solution.
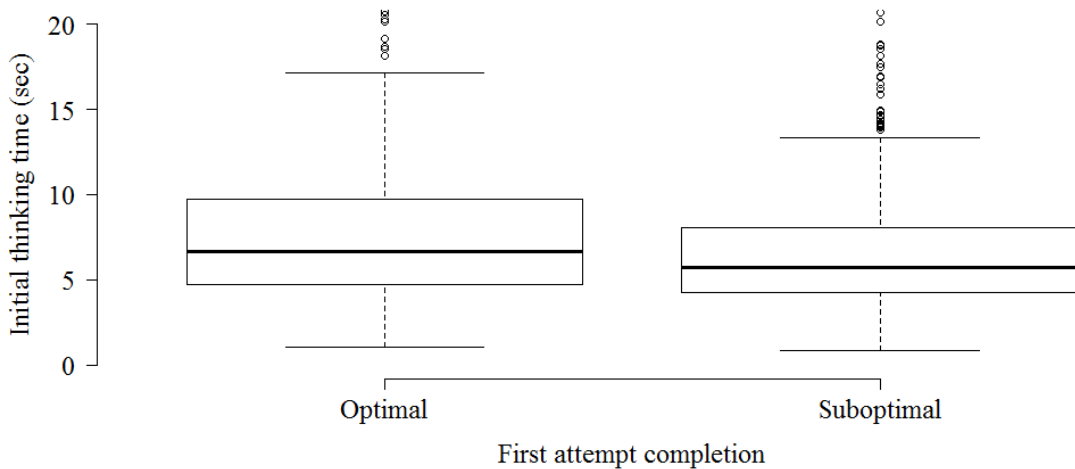
Figure 11. Boxplot of children first attempt completions and initial thinking time (sec).

The plot above shows that a trend may be emerging with respect to thinking time and planning efficiency. Children who spent longer planning their route were more likely to complete an item optimally (Median = 6.68s), relative to when a level was completed sub-optimally (Median = 5.57s). So, in the following analysis of children's moves, initial thinking time was added as a hypothesis variable. This includes the analysis of movement efficiency, and first attempt optimal completions.

Linear-mixed effects analysis of the move efficiency

In this analysis, I follow the same stepwise approach to the modelling procedures for initial thinking time and Item completion time, except that modality and initial thinking time were considered hypothesis variables. Modality could be treated in this way as the dependent variable movement efficiency was not confounded by time. Initial thinking time was considered to investigate the link between children's planning time and whether this influenced the number of moves they executed.

Investigation of the random effects structure of the data revealed that Modality contributed significantly to the random variance in the model ($p < 0.001$). The baseline model took the following composition:

```
Model (1) = Move efficiency ~ 1 + Group + Optimal number
of moves + (1|Participant) + (1|Modality)
```

Building on model 1, I first entered the hypothesis variable of Modality.

```
Model (2) = Move efficiency ~ 1 + Group + Optimal number
of moves + Modality + (1|Participant) + (1|Modality)
```

Comparing model 1 and 2 revealed that Modality significantly contributed to the variance in the number of moves ($p < 0.05$). So, Modality was added as a hypothesis variable. Next, I added the interaction Modality $\times$ Group as a hypothesis variable.

```
Model (3) = Move efficiency ~ 1 + Group + Optimal number
of moves + Modality + Modality*Group + (1|Participant)
+ (1|Modality)
```

Running an ANOVA between model 2 and 3 revealed that the interaction between Modality and Group did not contribute significantly to the variance in the model ($p = 0.23$), and consequently was omitted. In the next phase of modelling I added the interaction between Modality and Optimal number of moves.

```
Model (4) = Move efficiency ~ 1 + Group + Optimal number
of moves + Modality + Modality*Optimal number of moves
+ (1|Participant) + (1|Modality)
```

An ANOVA between model 2 and 4 yielded a non-significant effect ($p = 0.64$), so the interaction between Modality and Optimal number of moves was omitted. Finally, the hypothesis variable of Initial thinking time was added to the model.

```
Model (5) = Move efficiency ~ 1 + Group + Optimal number
of  moves  +  Modality  +  Initial  thinking  time  +
(1|Participant) + (1|Modality)
```

Computing an ANOVA between model 2 and 5 resulted in a near significant effect ($p = 0.06$). Therefore, Initial Thinking Time did not explain a significant proportion of the variance in the number of moves children took to complete each trial, and so, was omitted from the final model. Hence, the following regression table refers to the optimal predictive model, model 3.

Table 9

Best predictor model for children's move efficiency.

	β	PME	SE β	t-value
Intercept	2.39	10.91	0.16	15.13***
P3	-0.15	0.86	0.11	-1.40
3-move	-0.18	0.84	0.04	-4.65***
Keyboard	-0.17	0.84	0.04	-4.31***

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

PME = Predicted Movement efficiency.

Table 10

Random effects structure of children's movement efficiency

	Variance	SD	*p*
Participant	0.07	0.26	N/A
Modality	0.00	0.00	0.00***
Residual	0.19	0.43	N/A

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Linear mixed effects modelling of children's move efficiency revealed that the fixed effect of Optimal number of moves explained a significant portion of the variance

in the model, whereby children adopted less efficient move strategies when completing 3-move items, relative to 4- move items, $t = -4.65$, $p < 0.001$. Further, there was a significant effect of Modality, whereby children took less moves to complete an item while using the keyboard relative to the floor mat, $t = -4.31$, $p < 0.001$.

First attempt success

Another consideration in the analysis of the moves children executed were the factors that contributed to children's success rate on their first attempt. By coding optimal completions on the first attempt as 1, and sub-optimal completions on the first turn as 0, I investigated these parameters using Binary Logistic Regression. This analysis was performed using the glmer function. So, in the following analysis, I investigated the fixed, random and hypothesis variables that contributed to the probability of completing a trial in the optimal number of moves on the first turn. I named the outcome variable in this analysis 'Frist Attempt Success'.

Investigation of the random effects structure of the model revealed that neither Item nor Modality contributed significantly to the random variance in the model. Therefore, the baseline model consisted of the random effect of Participant and the fixed effect of Group and Optimal number of moves.

```
Model (1) = First attempt success ~ 1 + Group + Optimal
number of moves + (1|Participant), family = binomial
```

I then added the hypothesis variable of Modality, to determine if the device children used to complete the game influenced their planning performance.

```
Model (2) = First attempt success ~ 1 + Group + Optimal
number of moves + Modality + (1|Participant), family =
binomial
```

I then conducted an ANOVA between model 1 and 2. This analysis produced a near, but non-significant effect ($p = 0.06$). So, Modality was dropped from the model. Next, I added the interaction between Modality and Group.

```
Model (3) = First attempt success ~ 1 + Group + Optimal
number of moves + Modality*Group + (1|Participant),
family = binomial
```

An ANOVA between model 1 and model 3 showed that this the interaction between Modality $\times$ Group did not contribution significantly to the models variance ($p = 0.12$) and therefore was omitted from the model. Model 4 considered the contribution of the interaction between Modality and Optimal number of moves on the probability of getting a trial correct on the first attempt.

```
Model (4) = First attempt success ~ 1 + Group + Optimal
number of moves + Modality*Optimal number of moves +
(1|Participant), family = binomial
```

An ANOVA between model 1 and 4 revealed a non-significant effect, $p = 0.12$. Consequently, the Modality $\times$ Search interaction was omitted from the model. Finally, the I considered the effect of children's initial thinking time as conceptually children who spent longer planning their route may have been more likely to complete an item on the first attempt. Model 5 took the following composition:

```
Model (5) = First attempt success ~ 1 + Group + Optimal
number of moves + Initial thinking time +
(1|Participant), family = binomial
```

Comparing model 1 and 5 via an ANOVA between revealed a significant effect, $p < 0.05$. So, the regression analysis reported below were generated from model 5.

Table 11

Best predictor model for children's first attempt optimal completions.

	β	POFT	SE β	z-value
Intercept	-0.12	1.31	0.61	0.85
P3	0.22	1.19	0.14	0.10
3-move	-0.47	0.63	0.15	0.00**
ITT	0.03	1.03	0.01	0.04*

Note: * $p < 0.05$; ** $p < 0.01$.

POFT = Probability of an Optimal Completions on the Frist Turn.

ITT = Initial Thinking Time.

Table 12

Random effects structure of children's first attempt completions.

	Variance	SD	*p*
Participant	0.32	0.56	N/A

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The binary logistic regression revealed that the fixed effect of Optimal number of moves had a significant bearing on the children's first attempt success rate. Children were less likely to complete a 3-move item on the first turn in three moves (e.g. optimally), relative to 4-move items, $z = -0.47$, $p < 0.01$. Moreover, the longer children took to plan their route the more likely they were to complete an item optimally on the first attempt, $z = 0.03$, $p < 0.05$.

Number of invalid moves

As an indication of children's inhibitory skills, I also measured the number of invalid moves they committed while completing the task. Invalid moves are conceptually like 'rule violations' documented in other planning research. Rule violations in Slippy's Adventure were those occasions when children attempted to make a move that was not

possible, such as toward a lily pad that was not accessible given the possible directions Slippy could move in (i.e. forward, backward, left and right), and, those occasions that children attempted to jump into the water, and not onto a lily pad. Table 13 provides the descriptives for this variable.

Table 13

Frequency of invalid moves, valid moves, and percentage invalid moves (%).

	Invalid moves	Valid moves	% Invalid moves
Year Group			
P1	485	2170	22.35%
P3	440	2443	18.01%
Optimal number of moves			
3-move	442	2086	21.19%
4-move	483	2527	19.11%
Modality			
Floor mat	635	2406	26.39%
Keyboard	290	2207	13.14%

Binary logistic regression analysis of move validity

To determine those factors that significantly contributed to children's move validity a binary logistic regression was performed. Coding for the analysis was as follows: Valid moves = 1; Rule violations = 0.

Defining the random effect structure of the model highlighted that both Item ($p < 0.05$) and Modality ($p < 0.001$) significantly contributed to the random variance. So, the baseline model took the following composition:

```
Model (1) = Move validity ~ 1 + Group + Optimal number
of moves + (1|Participant) + (1|Item) + (1|Modality),
family = binomial
```

In model 2 I entered the hypothesis variable of Modality.

```
Model (2) = Move validity ~ 1 + Group + Optimal number
of moves + Modality + (1|Participant) + (1|Item) +
(1|Modality), family = binomial
```

An ANOVA between model 1 and 2 revealed that Modality significantly contributed to the variance in the model ($p = 0.01$). So, Modality was added to the model. For model 3 the interaction Modality $\times$ Group was added to the model. However, this model did not converge, suggesting that the variance attributed to Modality $\times$ Group had already been accounted for in the current models parameters. The same lack of convergence occurred when I attempted to enter the interaction Modality $\times$ Optimal number of moves. Lack of convergence for each of these hypothesis variables suggests that a significant portion of the variance attributed to Modality (the common variable in each interaction) had already been accounted for, either in the random or fixed effects variance of Modality in the model. So, I moved on to investigate the effect of Initial Thinking Time on the number of invalid moves committed.

```
Model (3) = Move validity ~ 1 + Group + Optimal number
of  moves  +  Modality  +  Initial  thinking  time  +
(1|Participant)  +  (1|Item)  +  (1|Modality),  family =
binomial
```

The final ANOVA between model 1 and 3 revealed a non-significant effect ($p = 0.20$). So, initial planning time was dropped from the model, and below I report the regression statistics from model 2.

Table 14

Best predictor model for children's invalid moves.

	β	Prob. IV	SE β	z-value
Intercept	1.11	3.03	0.54	2.04*
P3	0.12	1.13	0.17	0.49
3-move	0.09	1.09	0.11	0.38
Keyboard	0.64	1.89	0.08	0.00***

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Prob. IV = Probability of executing an invalid move.

Table 15

Random effects structure of children's invalid moves.

	Variance	SD	*p*
Participant	0.66	0.81	N/A
Item	0.03	0.17	0.03*
Modality	0.00	0.00	0.000***

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The results yielded a significant effect of modality, as children executed significantly more valid moves while using keyboard, $z = 0.64$, $p < 0.001$. There were no other significant effects.

DISCUSSION

The following experiment investigated the effect of embodied cognition on children's EF using a newly created planning task. Children from P1 and P3 completed the task using two different modalities: a floor mat and a keyboard. I analysed the effect that embodiment had on performance by analysing the effect modality had on five dependent variables: initial thinking time; item completion time; number of moves; first attempt optimal completions; and move validity. I predicted that, given the effect of embodied cognition reported in the literature that children would benefit from use of the

floor mat. That is, children's planning would be better in terms of time, and the number of moves taken to completion. I also considered the number of invalid moves children executed as an indication of their competence – the less invalid moves generated the better the planning.

The results revealed the developmental sensitivity of the task. Generally, children in P3 outperformed children in P1, taking less time to complete items and making less moves in the process. This finding is in line with extant studies of children's planning, demonstrating that even in the early years of education children's planning develops markedly (Kaller, Rahm, Spreer, Mader, & Unterrainer, 2008). Apart from these performance differences however, there were no other statistically different outcomes between the two groups, suggesting that some features of task performance were almost equivalent between the two groups.

Neither group showed a dominance in their ability to complete a trial optimally on the first attempt. Although P3s showed that they could plan their route faster, this increased processing speed did not translate to an increased probability of completing an item optimally. Conversely, longer initial thinking times were related to optimal completions for the sample. This finding challenges the literature of planning, suggesting that speed of processing in this task does not necessarily correlate with task efficiency. During the task instructions children were encouraged to take their time to plan their route. Children who took more time to carefully formulate a sequence of moves demonstrated mastery of the task. Other researchers of planning (e.g. Unterrainer et al., 2015) have omitted observations in accordance with the 3-sigma rule also referred to as the '68-95-99.7' rule. That is, observations that fall out with a standard deviation range, often 2.5SD either side of the mean, are removed from the dataset. However, I contend that the assessment of planning should not adhere to this logic as the time children take to plan (i.e. initial thinking time) predicts the probability of success. The descriptive statistics related to initial thinking time demonstrate that some children initiated their first move without consideration of the problem, taking less than 1 second, while others spent over 1 minute. By using LMEM, and modelling the data in the log space, I investigated the implications of a wide range of initial thinking times on children's task performance. Future work should consider analysing initial thinking time and planning time data in the same manner, as the analysis above allows the researcher to make inferences from a wide range of response times – with longer latencies not necessarily detrimental to planning.

Embodiment was equivocal in terms of their planning ability. The results indicated that children took less time to plan their route while using the floor mat. This effect however did not correspond to greater task proficiency. On the contrary, children took less moves to complete items while using the keyboard. This suggests that the differences in both cognitive and physical engagement between the floor mat and the keyboard significantly altered the manner that children approached the task. The reduction in initial thinking time demonstrates that children showed greater levels of impulsive decision making on the floor mat, leading to fewer optimal completions while using this device. Moreover, an investigation of children's move validity found that children (particularly the P1s) were more prone to making invalid moves, by attempting to move the frog into the surrounding water, or to land the frog on a lily pad that was not accessible, while stepping between the padded squares of the mat. This pattern of performance suggests the processes that underlie movement planning, such as behavioural inhibition, is critical to success on this planning task. Behavioural inhibition, as noted by Barkley,

"…refers to three interrelated processes: (a) inhibition of the initial prepotent response to an event; (b) stopping of an ongoing response, which thereby permits a delay in the decision to respond; and (c) the protection of this period of delay and the self -directed purpose that occur within in from the disruption by competing events and responses (interference control)" (Barkley, 1997, p. 67)

Elements of Barkley's behavioural inhibition definition to an extent explains the pattern of performance shown by children in the experiment. The first and second element, related to inhibition of a 'prepotent response to an event' and 'stopping of an ongoing response', resonates with the strategy children adopted using the floor mat. Shorter planning times and an increased number of invalid moves signifies that while using this device, children felt less constrained; tackling the planning problem quickly, and attempting to navigate the frog in several directions – not necessarily in a manner that adhered to the rules of the task. Because of this, it could be said that children were more likely to disregard the rules and instructions I provided while using the floor mat relative to the keyboard. It is possible that the 'event' of moving from a padded square to another to move the frog caused children to become fixated on the movement they generated, and its onscreen consequence (seeing the frog move in the direction they had moved), rather than the requirements of the task. The last element of Barkley's definition related to a 'period of delay' for purposeful execution of an action links with the finding that

increased planning times led to an increased probability of first attempt optimal success. One aspect however that is not accounted for in Barkley's definition is the interference that embodiment had on children's decision making. Being afforded the opportunity to move like the virtual character in a task – in a video game like format – was clearly detrimental to children's capacity to stay focussed on the task. This is an important finding as we move toward an age where instructional materials are becoming digital and immersive. The type of interaction afforded to the user and their ability to follow rules in the learning environment should be given consideration. 'Embodiment' does not necessarily lead to better performance outcomes. A recent investigation of the sentence compatibility effect failed to demonstrate the benefit of action congruency on performance in several experiments (Papesh, 2015). Achieving the beneficial effects of embodiment on task performance does not simply involve creating an analogous task condition that affords actions congruent in the real, or virtual world. However, it is also possible that children's inhibitory problems in the floor mat related to the task's presentation.

Making irrelevant actions to repeat frog animation

One possible reason for children's preference for the keyboard is that using the electronic floor mat required a high degree of self-control, especially given the animation of the frog on screen. Several participants became excited after witnessing the affect they could have on the frog's direction, and instead of taking a measured approach, were more inclined to jump on any of the lily pads. I propose that this effect is linked to children's propensity to imitate actions; that making the frog jump became the objective of the game, and that they lost sight of the true goal. Several studies have shown that young children generate task strategies based on their observations of others. This is also the case for tasks wherein the experimenter deliberately performs an action that is counter-productive to achieving the end-goal. Freier, Cooper, and Mareschal (2015) included both goal-relevant and goal-irrelevant movements in their demonstration of a sequence of actions to children aged 3-5 years. In one condition for example, the experimenter shows the children how to make a sandwich, an activity that is interleaved with both relevant actions (e.g. opening a jar of jam) and task irrelevant actions (e.g. scooping a spoonful of jam into a bowl and mixing it). The children are then asked to complete the same task, and the extent that they remained on task was examined. Both groups were susceptible to the influence of task-irrelevant actions, but importantly, that children aged 5 years were more

likely to engage in a distractor action. In the following experiment, I believe that a similar effect was witnessed, without the presence of a human experimenter. Instead, children in both groups observed the action of the frog hopping across to other lily pads and became distracted by this animation. The action of the frog jumping from one lily pad to another is not critical to the completion of the task, in the same way that stirring jam in the mixing bowl before spreading it on bread is not a necessary part of the task. Hence, a future measure that I will take to revert focus from the frog animation will be to place greater emphasis on the planning element of the task. This can be done by ensuring that participants pay attention to the move counter in the top left corner of the screen prior to starting a block of trials. Another possible explanation for children's performance on the floor mat could relate to the tasks setup.

Working memory potentially exacerbated by task setup

In the task, children spent a lot of time looking at their feet, switching back to the screen, and back to their feet again before making a move. The setup of the experiment did not support ease of attentional shifting between floor ant screen, as the floor mat and computer screen were almost at a 90-degree angle to one another. This is an important limitation of the experiment as it raises the issue of children's working memory on their planning performance. To successfully complete a level in Slippy's Adventure children had to first look at the configuration of the problem on screen and break that problem down into the constituent moves. To complete a trial successfully without stagnating, children had to hold this sequence of moves in memory, and then perform that set of actions using the matching directional keys on the floor mat. Thus, completing a trial while using the floor mat required more working memory to use of the keyboard. While completing the task with the keyboard, children were able maintain focus on the computer screen and execute button presses simultaneously. So, the working memory demands between each device were quite different. Indeed, studies of children's working memory have shown that children's action planning suffers when required to switch between different tasks, as opposed to repeated execution of the same action (Baddeley, Chincotta, & Adlam, 2001). In this experiment, using the floor mat forced children to stop and update their planning sequences on-the-fly. On reflection, this suggests in the floor mat version of the task, working memory demands were too high. It is possible that removing the need to switch between the screen and the floor mat may lead to better strategy formulating, by reducing working memory load. Thus, in the next version of the task I will reduce the

demands on working memory by moving the screen to the same plane as the floor mat, onto the floor.

Additionally, the stop-and-check strategy that children adopted while using the mat also indicated that an effect of action congruency could be confounded by the tasks setup. In previous experiments of action congruency, the participant responds in a manner that resembles the real-world action, thereby retrieving sensorimotoric information pertaining to that movement from memory. In the following task, children's performance was to be influenced by their knowledge that frogs hop, and that by using the mat they could simulate the actions of a virtual character. However, frequently needing to stop and switch visual attention between the screen and the floor mat likely prohibited this sense of embodiment, as movements would become less frog like and more procedural in nature. Future investigations of embodiment with virtual characters should therefore examine the qualitative nature of the user's movement, to determine whether actions congruency is being achieved from the tasks design.

From a technological perspective, performance differences between the floor mat and the keyboard may also have related to the configuration of each devices directional buttons. On the floor mat the directional keys are presented on a 3×3 grid, whereas on the keyboard the directional keys are laid out near, with the 'Forwards and 'Backwards' keys directly above and below one another. This is important particularly when considering how movements would be executed on each device. While using the floor mat, children were encouraged to return to a centre neutral square between moves, therefore allowing them to plan their next move. This 'return to centre' necessity was not required while using the keyboard. Instead, children could rest between each move by simply moving their fingers away from the directional keys. So, the intermediate stage between moves was quite different for each device. Also, if children wanted to direct the frog downwards while using the floor mat they often visually turned around to visually check the location of the 'Backwards' square before moving to it. The same action on the keyboard could be considered much simpler, as children had to navigate their finger to the 'Backwards' key located directly below the 'Forwards' key. In sum, the type of movement planning between each device differed significantly due to their configuration and motor skill requirements. I accounted for this difference in the next experiment by creating matching movement button configurations, and presentation.

CONCLUSION

The research of embodied cognition suggests that action congruency can enhance information processing. In a planning task, this would be represented by an increase in initial thinking time and a reduction in the number of moves taken to complete a task. In this experiment, children, completed a planning task with two devices, one of which – a floor mat - afforded children the opportunity to generate actions congruent to a virtual character. However, achieving action congruency with a floor mat requires careful consideration of the type of actions afforded by the mat, and how they relate to the content of the task. While completing the planning task on the floor mat children demonstrated that this technology can be more challenging, in terms of maintaining task focus and rule adherence, relative to a traditional technology (a PC keyboard). In the following experiment, I aimed to account for differences in modality in terms of presentation and movement execution, to achieve greater parity, and a better sense of embodiment.

CHAPTER 4 – EXPERIMENT 2

In my first experiment, I examined the effect of embodied cognition on children's EF. Specifically, children were asked to complete a newly created planning task using two different modalities: a floor mat that was considered the embodied interface, and the less embodied keyboard. The former was more embodied, as congruous actions have shown to reduce processing speed (Glenberg & Kaschak, 2002), and also, that giving children the opportunity to use their mind and bodies can have advantageous effects on their understanding of a task (Manches & O'Malley, 2010). In the less embodied condition, children completed the task using a keyboard; a device that could be considered to require a higher level of abstraction as finger presses did not match the jumping action of the frog.

The effect of modality on performance

Augmenting a floor mat with a planning task provided interesting conclusions about the way children conceptualise a task when the response format is manipulated. Interestingly, children spent less time planning their route using the floor mat, and this difference was significant for P1s who showed elevated initial thinking times using the keyboard. This was somewhat surprising given the different motor processes required for use of each device. I expected that, regardless of the task demands, children would take longer to complete the task while using the floor mat as the motor coordination demands were higher: children had to stand upright and move their feet between a set of padded squares. In contrast to this gross motor activity, use of the keyboard required fine motor skill and precise finger presses. Moreover, the reduction in initial thinking time did not result in better performance, as children were more likely to complete a trial in the optimal number of moves on the first turn while using the keyboard. This performance pattern raises several questions.

Baseline EF

First, it appears that children were less able to inhibited their actions while using the floor mat relative to the keyboard. To determine if inhibition was a significant factor in this phenomenon I added a bassline cognitive assessment of EF, the Behavioural

81

Assessment of Dysexecutive Syndrome for Children (BADS-C; Emslie, Kalff, & Krabbendam, 2003) to the following experiment. The BADS-C is a paper pencil battery of EF tasks derived from the adults Behavioural Assessment of Dysexecutive Syndrome (BADS; Wilson, Alderman, Burgess, Emslie, and Evans, 1996). The BADS-C was developed to assess children on a range of EF skills including problem solving, perseverative behavioural, snap decision making, behavioural modification based on changes in the environment, and planning. Many of the subtests in the BADS-C share commonalities with the cognitive and motor requirements of Slippy's Adventure. In the following section, I describe each of the BADS-C subtests and describe how the cognitive skill required maps on to this experiments planning task.

BADS-C Subtests

The Playing Card Test

In this test children are presented 20 playing cards and first asked to respond to each card as quickly as possible by first saying, "'Yes' to red and 'no' to black". These instructions are placed is full view for the duration of the task. In the second part of the task children are shown the same set of cards again but this time are asked to say, "'Yes' if the card is the same colour as the one before it. Say 'no' if the card is a different colour from the one before it". Scores are marked in terms of the number of perseverative errors produced in the second turn, e.g. if a child says 'yes' to a card based on the first sorting rule (based solely on its colour) and not the new sorting dimension (colour and order). So, a high score on the Playing Cards test indicates that the child made many perseverative errors.

Performance on the Playing Cards Test is considered as an indication of children's cognitive flexibility, or set-shifting. Adept cognitive flexibility is marked by the ability to change sorting dimension accordingly, and thus requires the child to keep in mind the rules of the task, and to update those rules if the rule is to change. In Slippy's adventure children had to keep track of the number of moves they were aiming to complete the game in by attending to the number presented in the top left hand corner of the screen. This number changed without explicit instructions from the experimenter, and so it was up to the child to update their strategy, and shift from seeking three-move routes to four-move routes. Keeping this information in mind proved challenging from the outset, as the results from experiment 1 indicate that children were less proficient at the first ten trials (3-move problems) comparatively to the last ten trials (4-move problems).

The Water Test

In the Water Test, children are presented with a plastic base holding a cylinder half-filled with water, covered by a lid with a small hole in the centre, and a tall slim glass tube with a cork inside, at its base. Separate from this apparatus are three tools: a metal wire with a crochet hook at one end, a threaded plastic tube, and a screw top lid. Children are told that the aim of the game is to remove the cork from the glass tube using the tools provided (i.e. the items separate from the base). The rules are that they cannot lift anything – apart from the tools – with their hands, including the glass tube, cylinder, and main base.

Scoring on the water test is marked in accordance to a set of predefined stages that lead to successful retrieval of the cork. Children only score points for stages they complete themselves. Prompts can be provided by the experimenter if a period of 65seconds passes without progress.

Hence, the Water Test is an assessment of children's motor planning. Success in the task requires breaking down of the problem into a set of logical steps that move closer to a goal state (i.e. to retrieve the cork). Each of these steps or operators are motoric in nature; they require children to think in terms of action, and the affordances offered tools in their environment. In Slippy's adventure, children must break down each trial in terms of a set of motor actions to be made. This will be a sequence of jumps that follow the rules, and logically lead to the route involving the fewest moves.

The Key Search Test

For the Key Search Test children are given a sheet of paper marked with a large square. They are provided with a story for the task: 'to pretend that they are a farmer, and that the square represents one of their fields. Somewhere in the field they have lost their keys, that you have been all over the field, and that the only thing you know if that the keys are definitely somewhere in the field'. Children are then given a pen and asked to mark out on the square the path they would walk to look for their keys, to make certain they will find them.

Marks are awarded based on the search strategy adopted by children. A search strategy that begins at one corner and zig zags across to the opposite corner (covering the area within the square) is awarded full marks. Less consistent paths would not be

considered time efficient, and effective for a search are awarded less marks (e.g. a path that spirals in each of the squares four quadrants). There is no time limit to the task.

So, the Key Search Test is like Slippy's Adventure in that children must think carefully about the most efficient route to take prior to executing it. This involves a visual analysis of the problem, in the case of Slippy's Adventure, a careful assessment of the lily pad configuration to identify the most efficient route.

The Zoo Map Test 1 and 2

In the Zoo Map Test 1, children are shown a map of a zoo and all the animals are listed. They are told that they do not have time to visit all the animals in the zoo just those that are pictured in the instructions. The instructions also detail the rules of the task: to start and finish at specific locations, to use dotted paths only once but white paths 'often as you like', and to only take one ride on the camels (a section of the map marked with pictures of camels).

Children score on the Zoo Map task is derived from their ability to follow the rules, use the rules to inform their route planning, and to follow a certain path from start to finish (there are two possible choices). Deviation from the optimal routes is penalised, as well as visiting animals not listed in the instructions and straying off the marked path. There is no time limit to the task.

The Zoo Map Test 2 is the same as version 1, only this time, children are given a set order which to visit the animals. Children are penalised for taking more than 25sec to plan their route, and for taking more than 130sec to complete the task.

Both the Zoo Map Test 1 and 2 closely resemble the format of Slippy's Adventure in that they are tests of route planning. The Zoo Map Test 1 even more so, as children are not given guidance on the order of places to visit (as is the case with the Zoo Map Test 2), but are asked to navigate across the map of the zoo in accordance to a set of rules. Because of this 'ill-structured' nature to the Zoo Map Test 1 (White, Burgess, & Hill, 2009), I consider this task be closest in its composition to Slippy's adventure.

The Zoo map tasks are also completed with the instruction in full view of the child. This measure is taken to reduce the working memory load of the task, and to allow children to focus on route planning. Inspired by this protocol I too added a set of

instructions that outlined the rules of the game for children to observe as they completed Slippy's Adventure.

Six Parts Test

In this task children are given a set of 3 tasks (Green, Blue, and Red), each with 2 parts, i.e. 6 Parts. The Green involved simple mathematics (e.g. counting). The Blue task tests language (e.g. write the name of the object). The Red task requires physical sorting (e.g. place all the hoops into the lid of thee box). Children are told that they have 5mins to complete as much of the 6 tasks as possible. They are instructed to change colour after each task, and that they are not expected to complete everything from each task element.

Marks are awarded for children's ability to interleave different task elements, follow a repeated pattern, and use the time they have strategically.

Slippy's Adventure is also a task requiring a degree of multi-tasking, in that children must remember to execute moves while obeying a set of rules, keep updated with the number of moves to make by attending to the number presented in the top left hand corner of the screen, and to do so in a manner that reflects planning ahead – by careful assessment of the trials configuration.

Componential structure and validity of the BADS-C

The skills underlying successful completion of the BADS-C subtest has become a matter of debate in the psychological literature. These studies are important as they provide an indication of the executive abilities mediating performance on subtests, and overall on the BADS-C. Factor analysis of the tests structure have found a two-factor model, with scores on the Zoo Map Test 2 and Six Parts Test mapping onto one factor, and the Playing Cards, Water Test, and Zoo Map 1 mapping onto another (Willner, Bailey, Parry, & Dymond, 2010). Further, Willner et al. (2010) found that the Key Search Test did not map on either component. A study looking at age related differences in BADS-C performance found significant improvements between the ages of 8yrs -9yrs 11months, 10yrs-11yrs 11months, and 12yrs-15yrs (Engel-Yeger, Josman, & Rosenblum, 2009).

Thus, the BADS-C was chosen as a baseline assessment of children's EF in the following experiment. This battery would provide an indication of children's EF prior to

assessment, thereby affording the opportunity to investigate the relationship between EF and performance on Slippy's Adventure. Each of the subtests within the BADS-C mapped onto the skills required for Slippy's Adventure the Zoo Map Test 1. Importantly, the BADS-C is appropriate for children over the age of 7 years. Because of this, and for reasons explained in the following section, I decided to focus on one age group for the following experiment, children in primary 3 (starting age 7 years).

Focussing on embodiment

A notable effect shown in the previous experiment was age. Children in P1 spent more time planning their route across the pond, but took more time to complete trials relative to P3s. Further, the results showed that children in P3 completed trials in fewer moves, and were more likely to complete trials in the optimum number of moves on the first attempt at both times of testing. So, children in P3 outperformed children in P1 on the planning task in several aspects. Thus, the results indicated that the cognitive underpinnings of planning develop rapidly between the ages of 5 and 7 years, but did not demonstrate a beneficial effect of embodiment. This analysis represented a challenge that would alter the course of my investigation. While age related differences in performance were interesting to observe, the primary focus of this thesis was to examine the effect of embodiment and embodied technologies on performance. In the embodiment literature, many have argued that cognition is grounded by physical experiences, and is therefore sensorimotor in nature. It is likely therefore that differences between the two modalities in the first experiment signified differences in bodily experience; that the younger children were in the process of acquiring the cognitive tools necessary to represent information in the motoric manner. So, rather than recruit the same age groups for the following experiment, I focussed solely on the performance of a group of 7 year olds to generate a better understanding of how embodiment may affect performance. In the following experiment, qualitative analysis of video footage was conducted to reveal more about the nature of the movements executed by children. Thus, this investigation is a closer look at the effect of embodiment of children aged 7.

Children's IQ

The planning task developed for the first experiment was built on the logic of the Towers of London Task. Different degrees of optimal number of moves were

incorporated to force children to carefully analyse a set of map style configurations, affording me the opportunity to examine the effect of optimal number of moves on planning. However, the task had not yet been validated against an established task of EF. The inclusion of the BADS-C allowed me to do so, as I could attempt to draw relationships (e.g. correlations) between children's performance on this battery of tests with their performance on Slippy's Adventure. In the process of validating the task, I recognised that other factors, such as children's IQ could also have an impact on their performance on the task. Studies looking at the relationship between EF and IQ have shown that working memory, predicts adult's intelligence, but that other EF components such as inhibition and cognitive flexibility do not map onto measures of IQ (Friedman et al., 2006). More recently, Brydges, Reid, Fox, and Anderson (2012) found that when considered as a unitary construct EF mapped strongly onto children's intelligence (including a group of 7 year olds). Considering the research suggesting that EF and IQ share similar skill-sets, here I also tested children's IQ using the Wechsler Abbreviated Intelligence Scale 2nd Edition (WAIS-II; Wechsler & Chou, 2011). Below I provide a description of each of the WAIS-II subtests, and how each potentially map on to skills underlying completion of Slippy's Adventure.

The WAIS-II Subtests

Block Design

In the Block design subtest, children were given a set of blocks. On each side of the block was either white, red, or both white and red. The tests trials require the participants to match red and white pattern configurations. Initial trials are completed by the experimenter to demonstrate the tasks requirements. Scoring is marked by time and accuracy of participant's configurations.

The block design test requires participants to manually manipulate a set of blocks to reach a certain goal state. So, children are required to think in terms of their actions, and create their own strategy to complete the test successfully. This is like the planning task administered in the experiment 1 as children also had to think in terms of the actions they were about to make, albeit, their strategy faced greater restrictions in Slippy's Adventure due to the rules.

Vocabulary

In the Vocabulary subtest children are asked to describe a word said by the experimenter. Marks are awarded based on the on the conciseness of responses and semantic relatedness. Trials stop after three consecutive incorrect responses.

This subtest does not relate conceptually to Slippy's Adventure, and so, I did not expect to see a relationship between vocabulary and scores on the planning task.

Matrix Reasoning

For Matrix Reasoning, children are shown a series of patterns from a flip book. Each pattern has a missing part, and a choice of possible candidates to complete the pattern. Marks are given for correctly chosen pattern elements, and the testing stops after three consecutive incorrect trials.

Matrix reasoning is like Slippy's Adventure in that children had to process visually presented stimuli and determine the optimal choice from a select set: e.g. from the arrangement of lily pads in each trial. In the Matrix reasoning, children must choose from a set of possible images that which fits a missing piece of a visual puzzle. So, elements of choice and pattern matching are evident in each task.

Similarities

In the Similarities subtest children are asked to state the nature of the relationship between a set of picture and words. Scoring is based on the child's ability to recognise the semantic characteristic that conceptually links the items.

Like vocabulary, this subtest was not related to the requirements of Slippy's adventure, and so, I did not expect to see a relationship between this subtest and their planning performance. Scores on the WAIS-II are collated and converted into standard scores using population norms. These standardised scores yield three components to intelligence: Perceptual Reasoning (from a combination of scaled scores on the Block Design and Matrix reasoning subtests); Verbal Comprehension (combined scaled scores from the Vocabulary and Similarities subtest); Full scale IQ (FSIQ; a combination of scaled scores from each subtest). So, given the potential similarities between Slippy's Adventure and the Perceptual Reasoning score and subtests, scores generated in these areas of functioning were examined in relation to children's planning performance.

<u>Children's experience with technology</u>

A final factor that was considered in children's performance on the task was their familiarity with technology. Differences between age groups and trials in the task may have related to a child's frequency of computer game play at home. There may even have been some children who had used a floor mat before, and so, were more able to use the device from the outset of the experiment. To account for this potential variance parents were asked to fill out the Research Questionnaire on the Impact of Technology on Children.

This parent report questionnaire contains 24 items related to children's background (e.g. How old is your child?), use of technology (e.g. How many hours does your child watch television or DVDs each week?), after school activities (e.g. How often does your child read or is read to per week?), sleep patterns (e.g. At what time does your child go to bed on a school day?), and behaviour and emotions (e.g. Does your child show any change in behaviour when they play on the computer?). Responses are provided on a range of scales for each item or qualitatively, depending on the descriptive nature of the item. For example, responses to the item 'How many hours does your child watch television or DVDs each week?' are provided on a three-point Likert scale of a) 1-10 hours; b) 10-19 hours; c) 20 or more hours. Items such as 'What type of video games does your child play?' provide a line for parents to provide details of their child's favourite game. Of specific interest in the following research were items pertaining to children's technology experience. This included the following items:

- How many hours does your child watch television or DVDs each week?
- How many hours each week does your child play video games, e.g. PS3, Xbox, Wii or play internet games?
- How many hours each week does your child play on a portable console, e.g. iPad, iPod, PSP, Nintendo DS?

These items were considered as it is possible that children's performance on the task reflected their familiarity technology and video games, rather than EF specifically.

Optimal number of moves modification

The results from experiment 1 indicated that manipulating the problems complexity in terms of the optimal number of moves did not affect performance in the expected direction. Children were more likely to complete 3-move trials on the first

attempt in the optimal number of moves to trials that included 4-move configurations. Further, initial thinking time has previously shown to increase with task complexity (Nitschke, Ruh, Kappler, Stahl, & Kaller, 2012), a finding that was not supported. The different patterns of performance documented raised questions about the validity and nature of the design. It is possible for example, that having completed ten 3-move trials children were then more adept at the following 4-move trials (i.e. the pattern of performance reflected practice effects). So, the following experiment added two more levels: 5-move and 6-move configurations, and reduced the number of trials in each level to four. The addition of two extra optimal number of moves would provide a new level of challenge to children, and add to the literature of planning ability in this age group.

Practicalities studying embodiment with a floor mat

Firstly, the indication that children took less time to plan their route while using the keyboard is somewhat surprising, given that the motor skill required to use this modality was less physically demanding than the floor mat. Use of the keyboard required fine motor skill, whereby children had to press their fingers onto the different directional buttons, depending on the direction they desired to move. In contrast while using the floor mat, children had to stand upright to step between the directional buttons on a padded floor mat, thus requiring a degree of gross motor skill. The data pertaining to children's initial thinking time on the floor mat indicated that there were five observations that took place prior to one second. These anomalies related to two factors of floor mat performance. The first, that some children found it difficult to keep their feet within the neutral square in the centre of the mat. Figure 12 below highlights this problem:

Figure 12. Floor mat with neutral square boundary highlighted

If children's feet slightly overlapped with any of the boundary lines of the other directional squares, this could initiate an unwanted move. Although children were given explicit instructions to keep their feet in the centre square after completing a trial, there were occasions that unwanted moves were executed. The data of invalid moves also highlighted that while using the floor mat, children tended to be less methodical in their approach.

Behavioural inhibition

All bar one child had used a floor mat before, and it is possible that a combination of the devices novelty, and the prospect of playing a videogame with it was highly motivating for children. Their enthusiasm however did not facilitate a patient, organised approach to the task. In experiment 1 I did not want to influence children's approach to using the floor mat too much, as this could have a significant impact on their strategy and planning. It was evident that after completing 10 practice trials, some children were motivated to jump between the squares in no specific order, but simply to jump around like a frog would. Although there was a clear indication that children experienced a degree of embodiment, in that their actions were congruous to the virtual character's, the effect did not facilitate children's attention to the task. In other words, children were more distractible while using the floor mat relative to the keyboard. After considering the data and observations from experiment 1 I developed a more stringent protocol to avoid children's propensity to jump randomly between the padded squares on the floor mat. An instruction sheet that was placed in full view for the duration of the experiment. Moreover, greater stress was placed on children's planning in the task. I provided more comprehensive verbal instructions to encourage children to carefully plan their route, to try to achieve the optimal number of moves, not to break the rules, and each were asked prior to both the practice trials and test trials if they understood the requirements of the task. I also made a few presentation modifications to improve children's ability to respond.

Changing visual perspective to reducing working memory load

One feature evident from my observations of children's floor mat performance was the difficulty children had switching visual attention between the display and position of their feet on the floor mat. This could have over loaded children's cognitive capacity,

or working memory, during developing a sequence of moves to execute. Working memory is said to play a crucial role in the retention of goal-directed information and resultant action execution (Ohbayashi, Ohki, & Miyashita, 2003). Indeed, investigations of physical movement, and its effect on visuospatial working memory, have shown that adding an action to a task that requires information to be retained can interfere with retention of task relevant information. Spiegel, Koester, and Schack (2013) showed that asking participants to place a ball onto a peg, as well as remembering the location of a target stimulus on screen reduced their spatial memory accuracy. Thus, I recognised that the layout of the experiment required modification to suit children's working memory ability.

All participants from experiment 1 repeatedly switched visual attention between the computer screen, placed on a table in front of them, and where their feet were currently positioned, to plan which square to move to next. This regular switching of attention demonstrated that the working memory demands of the task while using the floor mat may have been greater to that of the keyboard. While using this device, children had to process the configuration of the puzzle on screen, remember it, then look back to their feet and use that information in memory to inform the decision-making process (i.e. which direction to move in). Children did not have to change visual perspective as readily using the keyboard, and it was evident that some children were familiar with the layout and use of keyboard directional buttons. To reduce the working memory demands of the task, I changed the layout of the experiment. Rather than display trials on a screen 90° to the floor mat, the display was relocated to the floor, just above the floor mat (see figure 13).

Figure 13. New Layout of Slippy's Adventure

This new format allowed children to visually process the onscreen puzzle and the position of their feet, i.e. children no longer had to retain information about the configuration of the trial then attend to the position of the feet. The on-floor display was a 24" computer monitor. Setting up the experiment in this way somewhat resembled other interactive floor mat technologies that have started to emerge in the embodied cognition literature. For example, Lindgren and Johnson-Glenberg (2013) developed an interactive floor mat to teach physics students about gravity. Projectors displayed a dynamic display of the universe onto the floor including stars and planets. At one end of the display was a meteor that students could 'attach' themselves to, and therefore, control the movements and velocity of the meteor. The goal of the task was to guide the meteor to a certain location on the map of the universe, taking into consideration the gravitational pull of the planets displayed: the closer students guided the meteor to a planet, the more the meteor would be influenced by that planet's gravitational field and consequently move toward the planet's orbit or surface. Lindgren and Johnson-Glenberg (2013) found that students retained more information about their topic after participating in this form of 'embodied learning' to traditional paper and pencil learning materials, and, that students were more motivated to engage with physics after taking part in the meteor task. So, although the layout of the experiment had changed significantly, the setup did resemble other multimodal interfaces currently under investigation. Another method I used to reduce the potential processing differences between the floor mat and the keyboard was to match them in terms of appearance and configuration.

Overlaying keyboard keys with image arrow button

In experiment 1, children completed the task using a standard PC keyboard, and a floor mat. However, the layout of a standard keyboards directional keys is different spatially to that of the floor mat. Directional buttons on a keyboard are set out in a triangular formation, with the 'left' and 'right' keys flanking the 'down' button, and the 'up' button above the down key. On the contrary, the floor mat buttons are presented on a 3×3 grid, with a neutral central square (see figure 14). To account for these differences in button layout, in the following experiment children completed the task using the numberpad section of a standard PC keyboard, with each key overlaid with an image of an arrow to resemble the appearance of the floor mat.

Figure 14. Xbox floor mat (left); HP keyboard, number pad overlaid with direction icons (right)

Changes to the trial parameters

To create 5-move and 6-move levels, qualitative aspects of the task required modification. In its original composition, trials were created on a blank 5×5 grid. This grid was not large enough to support 5 and 6 move trials, and so, was expanded to 10×10. Thus, the stimuli in this next iteration were half the size to the previous experiment. However, on this occasion children had a better view of the problem, as it was presented to them on the floor in their field of view.

My observations and notes taken during experiment 1 informed me that children found the floor mat version of the task difficult for reasons other than the type of movement it afforded them. It was evident that although children showed signs of embodying the actions of the frog, the layout of the experiment prohibited their performance. Assessing the effect of interface on performance would also require changes in terms of task demands, as children were seemingly better at the more complex trial configurations, and to each modalities presentation, to ensure that children treated the

functionality of each device comparably. Hence, the predictions for this experiment remained the same to those in the previous experiment. However, I now focussed my attention to a single age group to better understand the effect of embodiment at age 7 years. I also collected information about the samples baseline EF, IQ and experience with video games, as it is possible these features fed into their performance. As mentioned earlier in the introductory chapter, videogame experience appears to mediate EF (Basak et al., 2008). So, an additional prediction here was that children with more gaming experience would show enhanced performance on an element of planning.

METHOD

Participants

Twenty pupils from a local Primary School (M = 7.15 years, SD = 2.98), including 9 females and 11 males, took part in the experiment. All participants had English as their first language, and were neurologically unimpaired. The experiment took place on school premises in a library, providing a quiet setting for testing. Upon completion of the experiment children were given a sticker, and thanked for their participation. The study was approved by Heriot-Watt University's Ethics committee, approval number: 2014:5.

Materials

Behavioural assessment of dysexecutive syndrome for children (BADS-C; Emslie, Kalff, and Krabbendam 2006)

The BADS-C is a child friendly EF battery consisting of six different tasks: 1) Playing Cards Test; 2) Water Test; 3) Key Search Test; 4) Zoo Map Test 1; 5) Zoo Map Test 2; 6) Six Parts Test (for a full description of see introduction).

Wechsler abbreviated scale of intelligence (WAIS-II; Wechsler & Chao, 2011)

The WAIS-II is an intelligence quotient (IQ) assessment with four subtests: 1) Block Design; 2) Vocabulary; 3) Matrix Reasoning; 4) Similarities (for details of each subtest see introduction).

The final grading of the WAIS-II yields three componental scores: Verbal Comprehension Index (VCI); Perceptual Reasoning Index (PRI) and Full Scale IQ. VCI is a culmination of the marks awarded from the Vocabulary and Similarities subtests. PRI is a combination of the scores achieved on the Block Design and Matrix Reasoning subtest. FSIQ considers scores from all four subtests. These scores are standardised based on population norms, and, provide a means to generate standardised scores for the six subtests on the BADS-C, and an overall BADS-C standardised score. The BADS-C booklet includes Normative Tables for children aged 7yrs – 7yrs 11 months, indexed by FSIQ. So, here I considered children's raw scores from the subtests of the WAIS-II and

BADS-C, as well as the WAIS-II normative indexes (VCI, PRI, and FSIQ), and their age scaled score on the BADS-C.

Research questionnaire on the impact of technology on children[5]

This parent report questionnaire comprises 24 items related to children's use of technology, extra-curricular activities, and behaviour (for details see introduction). In this experiment, the following items were of interest:

- How many hours does your child watch television or DVDs each week?
- How many hours each week does your child play video games, e.g. PS3, Xbox, Wii or play internet games?
- How many hours each week does your child play on a portable console, e.g. iPad, iPod, PSP, Nintendo DS?

Slippy's Adventure 2.0

In the introduction, I described some of the changes made to the task for this experiment. Here is a summary:

- While using the mat the display is placed on the floor in front of the mat
- Two extra levels of optimal number of moves were added, such that children now completed 3-, 4-, 5-, 6-move trials
- The grid upon which trials were generated was doubled in size to accommodate trials with optimal number of moves of 5 and 6-moves
- Minor aesthetic changes were made to keep children focussed on the position of the frog, and the task, such as the omission of a wavy border, and the addition of a lily pad in the top left corner of the screen to keep children focussed on the number of moves

The rules of the game were as stated in the previous experiment.

---

[5] Thank you to Dr. Jacqui Taylor (Bournemouth University) for providing permission to use this document.

Design

The study adopted a 2 × 4 within subject's design. The independent variables were modality (with two levels: floor mat, keyboard) and optimal number of moves (four levels: 3 move, 4 move, 5 move, 6 move). All children completed the game using each modality, with a two-week gap separating sessions. The same dependent variables were studied in this experiment: initial thinking time (sec), trial completion time (sec), number of moves, optimal completions on the first turn, and rule violations.

Procedure

Children were tested individually, at four separate sessions. Firstly, children completed the BADS-C. Testing time for this task took between 40-50mins. In the second session children completed the WAIS-II. Testing time for this cognitive battery took an estimated 40-50mins. In the last two sessions participants played SA, either using the floor mat or the keyboard (order was counterbalanced across participants). A two-week gap was given between completing SA at time 1 and time 2 to account for potential priming effects on performance. Further, the above order was adopted to avoid potential priming effects of the BADS-C on performance on SA, as each have similar task elements (e.g. route planning).

SA procedure

To start the rules of the game were explained. This list of rules included:

- Slippy can only jump onto other lily pads
- Attempting to reach the golden lily pad in as few moves possible. For this rule the I also explained that going over the number of moves as shown in the top left hand corner of the screen was ok, and to try to get to the golden lily pad.
- That Slippy can only jump forward, backward, left and right
- Slippy cannot jump in the water

After talking each participant through the rules and instructions the experimenter then demonstrated how to use the floor mat. Children were told only to use the pink (forward and backward) and blue (left and right) buttons, and not to attempt to use the silver corner

buttons, because 'Slippy cannot jump diagonally'. I stressed to begin each trial by having both feet placed in the centre of the mat on the 'Stay Cool' button.

Children were first given 8 practice trials. Each of these trials encouraged use of each directional key, and familiarised children with the rules of the game. Following the practice trials children then completed 16 trials. Trials were presented in four blocks each containing four levels. These Block were presented sequentially starting with 3 move problems, 4 move problems, 5 move problems, and finishing with 6 move levels. Trials were randomised within each block. Children were given three attempts to complete a trial. After each failed attempt the experimenter said to the participant, "Ok, you have two more tries. Remember to take your time and plan your route carefully". If they failed to complete a trial successfully after three attempts the trial was skipped. The management of data from trials is discussed at the beginning of the Results sections.

Qualitative analysis of floor mat interaction

        Children were video recorded during their completion of the task using the floor mat. This data was collected to determine the extent that children executed actions on the floor mat as if they were a frog, thereby providing an indication of action congruency. Additionally, these video data were analysed to investigate whether changes to the task parameters benefitted their engagement with the task. It was of interest for example whether children were switching visual attention between their feet and the task display, after moving to the display to a visible area.

Action simulation and congruency

        Of the twenty participants three showed a degree of action congruency, with a collective total of 12 frog hops. Frog hops were defined by as hopping movements between directional buttons using both feet. These occurrences, although rare, suggested that some children did embody frog like actions. For participant who did show this type of action, action congruency was achieved for a select number of trials, and in later trials changed to a more energy efficient method of stepping between keys.

Figure 15. Participant's making frog like jump between movement squares. Left: Participant 6. Right: Participant 7.

For the most part, the dominant strategy amongst the group was stepping between the movement buttons.

<u>Stepping between movement buttons</u>

Stepping between the movement buttons was the most popular form of interaction adopted by children. That is, the sample preferred to keep one foot in the centre neutral square and shift one foot to the desired directional key. It was evident that this strategy did not require as much energy as frog hopping.

Figure 16. Participant 8 and 9 stepping to directional button, the most common movement type executed in the games completion.

<u>Tracing route with finger</u>

Some children preferred to trace the route of their chosen path prior to starting a level. This strategy was particularly evident for the 5-move and 6-move trials, indicating that with an increase in Optimal number of moves, children felt the need to adopt a more comprehensive and deliberated planning strategy.

<u>Using one leg to stand, other to select buttons</u>

While adopting this method, children could keep their strategy consistent, however the movements made were unusual, such as crossing the 'moving' leg over and across the standing leg to access button closest to standing leg.

<u>Checking location of 'backward' button</u>

Perhaps one of the caveats of using the floor mat was that when children wished to move the frog backwards they needed to check the location of the backward square behind them. All children in the sample turned around to check the location to the 'backwards' square prior to using it. It could be argued that this action was detrimental to children's embodiment of the task, as it was an action that broke the congruency, between the actions they performed, and that of the frog.

Baseline cognitive and intelligence assessments

Below I provide the descriptives from both the BADS-C, WAIS-II and the Research Questionnaire on the Impact of Technology on Children.

Table 16

Means, range and standard deviations of the BADS-C and the WAIS-II.

Measure	Range	Mean	SD
BADS-C			
Playing Cards	0-10	2.81	3.29
Water Test	(-2)-10	4.36	3.47
Key Search Test	0-13	2.94	3.35
Zoo Map 1	(-8)-8	0.45	3.35
Zoo Map 2	0-9	6.27	2.29
Six Parts Test	3-16	10.75	3.53
Age Scaled EF	38-81	66.70	9.66
WAIS-II			
Verbal comprehension	68-127	95.65	13.42
Perceptual Reasoning	79-156	105.60	18.80
FSIQ	77-134	100.20	15.66

Research Questionnaire on the Impact of Technology on Children

Table 17

Frequency of children's technology use as reported by parents.

	Scale		
	1-10 hr(s)	10-19 hrs	20+ hrs
Hours/week watching TV/DVDs	15	3	1
	Scale		
	Never	1-5 hr(s)	6-10 hrs
Hours/week play video games	9	10	1
Hours/week portable video games	3	15	2

Of interest from this data was the amount of time children spent playing video games. Ten parents reported that their child played video games for between 1-5hours per week. Nine parents reported their child never played video games. Out of twenty, only one child was reported to play between 6-10 hours per week.

QUANTITATIVE ANALYSIS

Initial thinking time

Here, I provide the descriptives for children's initial thinking time in terms of Modality and Optimal number of moves. Given the non-parametric nature of the data, I report the minimum, maximum, median, and, the percentage of trials that were complete optimally on the first turn. Optimal completions were those instances when children completed a level in the fewest moves possible (e.g. three moves on a level with an Optimal number of moves of 3). For trials that took more than one attempt, the data taken related to children's initial thinking time on their first attempt, their Item completion time was an accumulation from their first attempt, and the number of moves was a summation of their attempted number of moves.

Table 18

Children's initial thinking time (sec) and first attempt trial completion (%).

	Min	Max	Median	First attempt
<u>Modality</u>				
Floor mat	1.14	88.67	6.41	54.15%
Keyboard	1.25	41.15	4.53	49.33%
<u>Optimal number of</u> <u>moves</u>				
3-move	1.14	88.67	5.11	68.10%
4-move	1.19	60.68	4.77	48.39%
5-move	1.26	77.42	5.93	39.30%
6-move	1.26	52.36	5.31	50.30%

Initial thinking time distribution

　　　　To begin the analysis, I generated a histogram of children's initial thinking time. This distribution included some outliers related to children taking a break; these were removed.
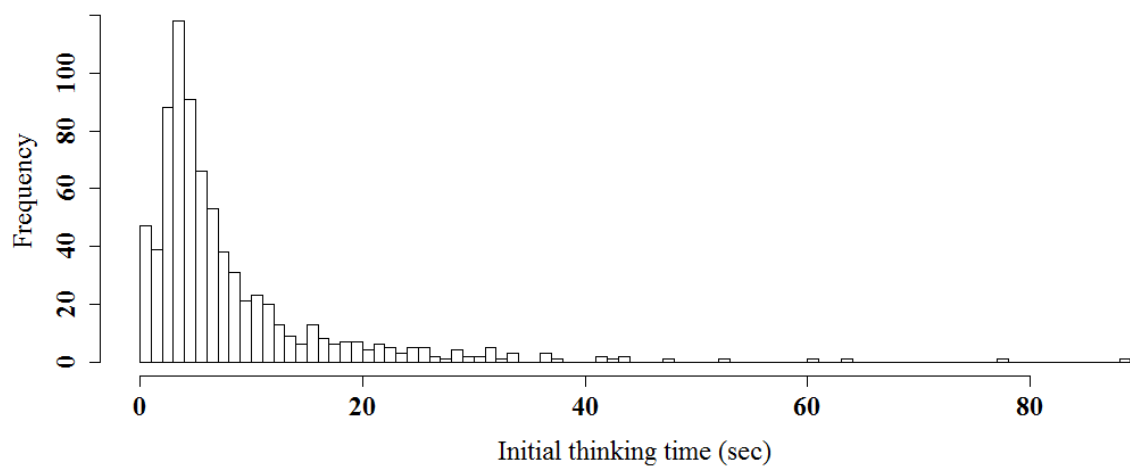
Figure 17. Histogram of initial thinking time distribution (sec).

A closer look at those observations that fell below 1sec revealed that on many occasions children's feet were accidently pressing a pressure sensor from another response pad. So, observations less than 1 sec were removed.
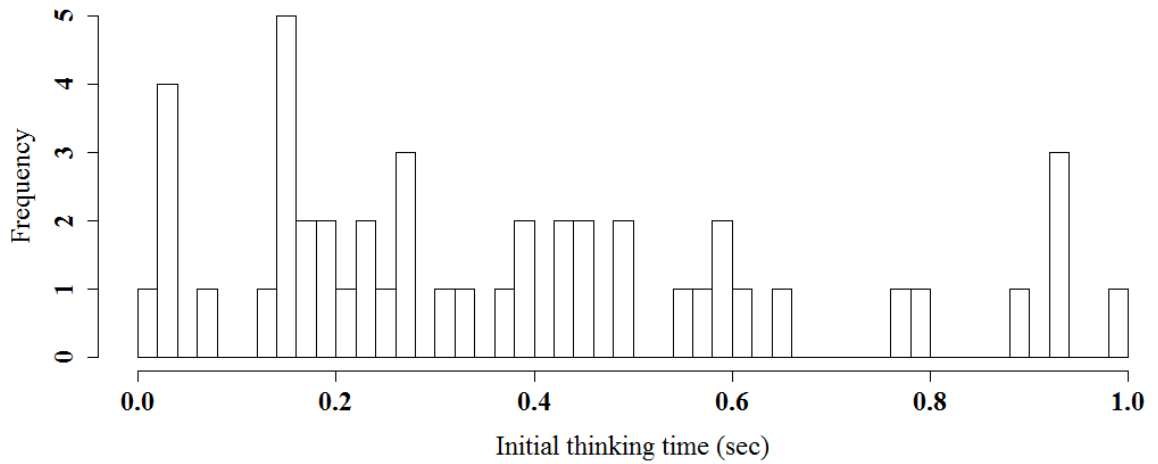
Figure 18. Initial thinking time less than 1 second.

To normalise the data for modelling, I took the log of observations falling between 1-100 seconds. Figure 19 below demonstrates this new distribution.
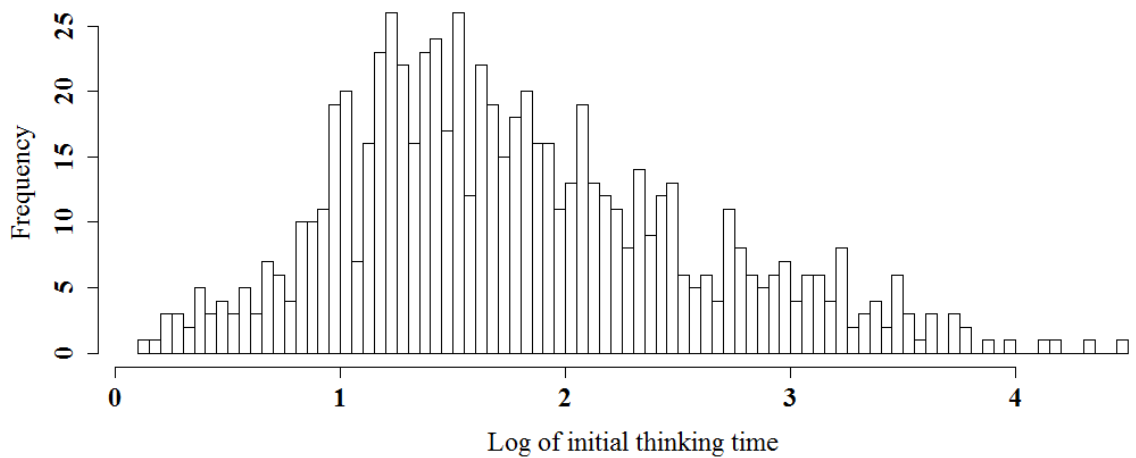
Figure 19. Histogram of the log initial thinking time for first time optimal completions between 1-100 seconds.

Initial thinking time analysis

The fixed effects for the following analysis was the factor 'optimal number of moves'. Each of the subtests and items from the BADS-C, WAIS-II, and Children and Technology Questionnaire were added as fixed effects once the random effects structure of the model was confirmed. The random effects examined in this analysis were the same as those investigated in experiment 1: Participant, Item, and Modality.

The hypothesis variables were Modality, and the Modality × Optimal number of moves interaction. Modality was considered as a hypothesis variable as the previous experiment's findings demonstrated that children did necessarily take longer to complete the task using the floor mat as predicted. However, the aim of the new presentation format of this experiment was to encourage children to take more time assessing the level configuration, now that they could view the level's configuration in its entirety without having to repeatedly switch attention. The interaction between Modality × Optimal number of moves would indicate that although the more challenging levels of Optimal number of moves would cause children to spend longer thinking about their first move, that this increase in time would be less on the floor mat relative to the keyboard (as the embodiment literature shows that processing speed benefits from congruent action).

Initial thinking time analysis

To begin, I drew out the random effects that contributed significantly to the random variance in the model. Regarding initial thinking time, the random effects of Participant, Item ($p < 0.05$), and Modality ($p < 0.001$) were inputted to the model.

```
Model (1) = log(Initial thinking time) ~ 1 + Optimal
number of moves + (1|Participant) + (1|Item) +
(1|Modality)
```

I then entered scores from each subtest sequentially to determine whether children's EF, IQ, or experience with technology significantly contributed to the variance in the model. This approach allowed me to identify the type of skills assessed in the planning task Slippy's Adventure. In the following description of each model I include only those fixed effects that produced a significant ANOVA result as there was a total of thirteen fixed effects to investigate. None of the BADS-C subtests caused significant levels of variance in children's initial thinking time. Children's score on the Matrix Reasoning of the WAIS-II did however:

```
Model (2) = log(Initial thinking time) ~ 1 + Optimal
number of moves + Matrix Reasoning + (1|Participant) +
(1|Item) + (1|Modality)
```

An AONVA between model 1 and 2 produced a significant effect ($p < 0.05$). So, children's scores on the Matrix Reasoning subtest were added to the model. No other subtest scores contributed to variance in the model. So, now I detail the hypothesis modelling. The first hypothesis variable I entered the model was Modality:

```
Model (3) = log(Initial thinking time) ~ 1 + Optimal
number  of  moves  +  Matrix  Reasoning  +  Modality  +
(1|Participant) + (1|Item) + (1|Modality)
```

Comparing model 2 and 3 with an ANOVA revealed that Modality significantly contributed to the variance of the model ($p < 0.05$). Therefore, Modality was added to the model. Next, I investigated the interaction Modality $\times$ Optimal number of moves:

```
Model (4) = log(Initial thinking time) ~ 1 + Optimal
number  of  moves  +  Matrix  Reasoning  +  Modality  +
Modality*Optimal number of moves + (1|Participant) +
(1|Item) + (1|Modality)
```

An ANOVA between model 3 and 4 yielded a non-significant effect. So, the Modality × Optimal number of moves interaction was omitted. The regression results reported below pertain to Model 3.

Table 19

Best predictor model for children's initial thinking time (sec).

	β	Predicted ITT	SE β	t-value
Intercept	1.58	4.85	0.20	7.77***
Keyboard	-0.37	0.69	0.07	-5.14***
4-move	0.03	1.03	0.15	0.19
5-move	0.23	1.26	0.16	1.50
6-move	0.07	1.07	0.15	0.45
Matrix Reasoning	0.03	1.03	0.01	2.14*

Note. *$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

Predicted ITT = Predicted Initial Thinking Time.

Table 20

Random effects structure of children's initial thinking time (sec).

	Variance	SD	p
Participant	0.07	0.81	N/A
Item	0.03	0.17	0.01*
Modality	0.00	0.00	0.00***
Residual	0.48	0.69	N/A

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Modality contributed significantly to the variance in the model, as children took longer to plan their first move while using the floor mat compared to the keyboard, $t = $ -

5.138, $p < 0.05$. The Matrix Reasoning subtest of the WAIS-II also contributed significantly to children's initial thinking time, whereby children who scored highly on this measure also took longer to plan their route, $t = 2.136$, $p < 0.05$. Of each level of Optimal number of moves, 5-move levels appeared elevate initial thinking time the most, with a near significant effect, $t = 1.504$.
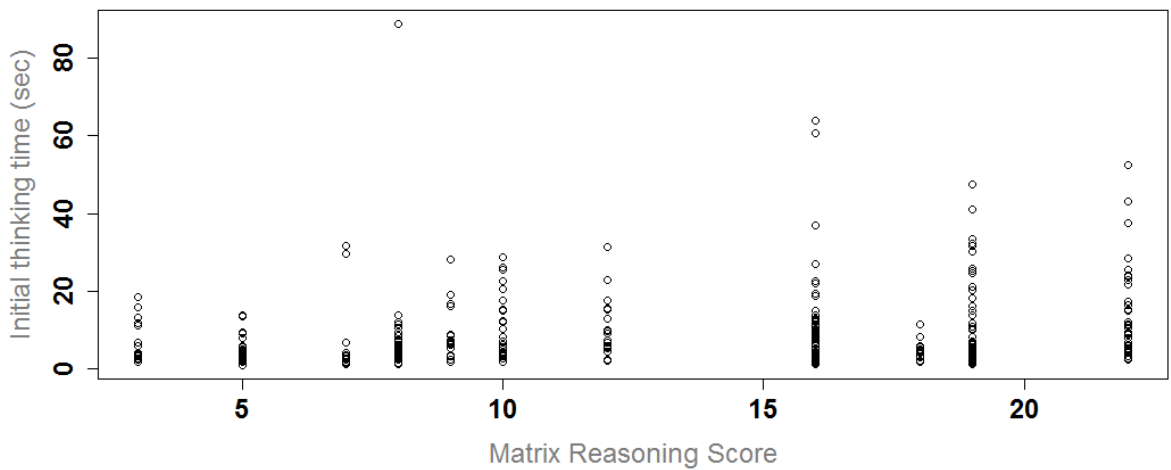
Figure 20. Scatter plat of Matrix Reasoning Score by initial thinking time (sec).

Item completion time

To begin the analysis of children's completion time I examined this outcome variables distribution.
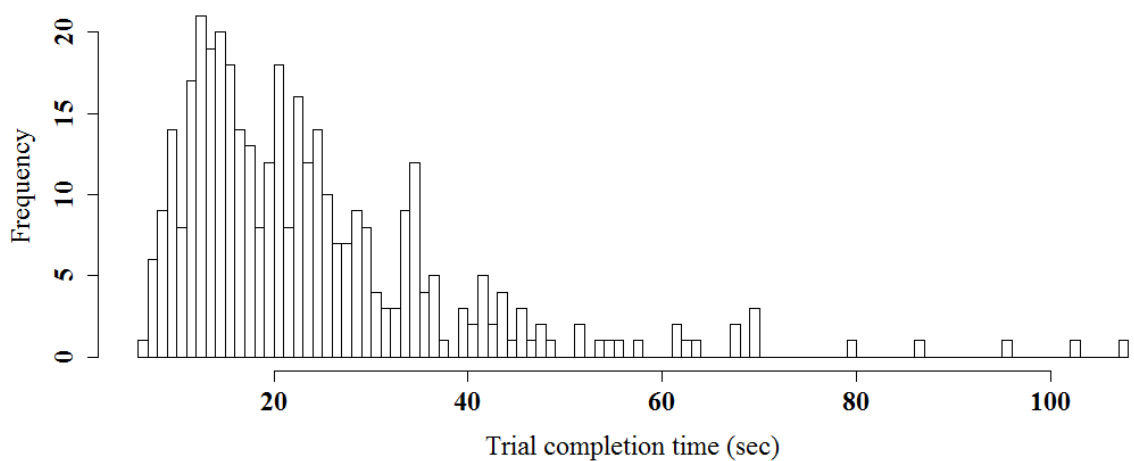
Figure 21. Histogram of children's item completion time.

As can be seen from figure 21 above the distribution of Item completion time was positively skewed to the right. I removed outliers related to those occasions when children took a break during the experiment. I then performed a log transformation on the data to generate a Gaussian distribution for modelling the data (see figure 22).
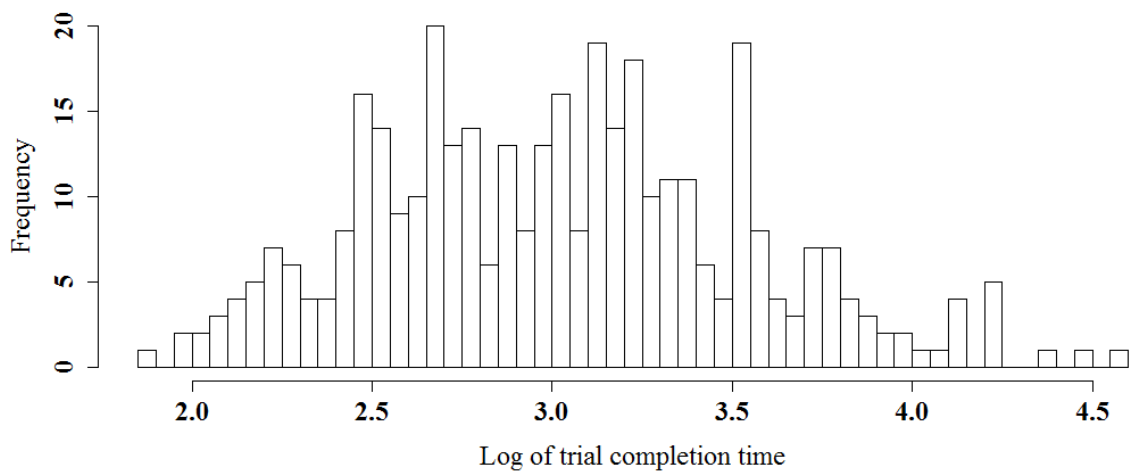
Figure 22. Histogram of the log of children's Item completion time.

Hence, the analysis conducted on children's Item completion time pertain to the log of this outcome variable.

Table 21

Range and median of children's item completion time (sec).

	Min	Max	Median
Modality			
Floor mat	8.14	95.81	22.69
Keyboard	6.66	69.23	16.40
Optimal number of moves			
3-move	6.66	95.81	13.31
4-move	7.39	51.34	19.84

5-move	9.30	69.39	25.67
6-move	9.15	86.10	24.62

Linear mixed effects modelling of children's Item completion time

The following analysis includes data from children's optimal completions, that is those occasions where children completed an item in the fewest possible moves. The fixed effects identified for this analysis included the effect of Optimal number of moves. In addition, I considered the hypothesis variable of children's Initial Thinking Time. This variable was considered as children who spent more time planning their route may well have taken less time to complete trials. As this dataset refers to those optimal completions, analysis of trial completion time for these observations gave me the opportunity to examined this relationship. Investigation of the random effects structure of the data revealed that both Item ($p < 0.05$) and Modality ($p < 0.001$) contributed to the random variance. So, these random effects were added to the baseline model alongside the random effect of Participant.

```
Model (1) = log(Item completion time) ~ 1 + Optimal
number of moves + (1|Participant) + (1|Item) +
(1|Modality)
```

The modelling process thereafter replicated that of initial thinking time: begin by inputting the scores from each subtest of the BADS-C and WAIS-II, and items from the Research Questionnaire on the Impact of Technology on Children individually, and testing their contribution to the models variance via ANOVA. This fixed effects analysis revealed that children's frequency of videogame play contributed significantly to the variance in the model ($p < 0.05$). No other fixed effects were identified, and so, the new model took the following composition:

```
Model (2) = log(Item completion time) ~ 1 + Optimal
number of moves + Hours/week play video games +
(1|Participant) + (1|Item) + (1|Modality)
```

In the next model, I input the hypothesis variable of Modality.

```
Model (3) = log(Item completion time) ~ 1 + Optimal
number of moves + Hours/week play video games + Modality
+ (1|Participant) + (1|Item) + (1|Modality)
```

An ANOVA between model 2 and 3 yielded a significant effect ($p < 0.05$), indicating that modality contributed significantly to the variance in the model. So, I added Modality to the model. The next hypothesis variable of interest was the interaction Modality $\times$ Optimal number of moves.

```
Model (4) = log(Item completion time) ~ 1 + Optimal
number of moves + Hours/week play video games + Modality
+ Modality*Optimal number of moves + (1|Participant) +
(1|Item) + (1|Modality)
```

Comparing model 3 and 4 via ANOVA revealed a non-significant effect ($p = 0.82$), so Modality $\times$ Optimal number of moves was dropped from the model. Finally, I considered the hypothesis variable of children's Initial thinking time. To recap, this data refers to those occasions that children completed an item optimally, and so, it is conceivable that these observations represent occasions that children were most careful planners.

```
Model (5) = log(Item completion time) ~ 1 + Optimal
number of moves + Hours/week play video games + Modality
+ Initial Thinking time + (1|Participant) + (1|Item) +
(1|Modality)
```

Comparing the variance of model 3 and 5 via ANOVA revealed a significant effect ($p < 0.001$). So, children's Initial Thinking Time entered the model. Model 5 was the final model; the regression analysis values are provided below.

Table 22

Best predictor model for children's item completion time (sec).

	β	PCT	SE β	t-value
Intercept	2.64	14.01	0.07	35.45***
Keyboard	-0.13	0.88	0.03	-4.47***
Video games 1-5hrs/week	-0.15	0.86	0.05	-2.87*
Video games 6-10hrs/week	-0.36	0.70	0.12	-2.88*
Video games never/week	0.03	1.03	0.12	0.26
4-move	0.24	1.27	0.08	2.82*
5-move	0.50	1.65	0.09	5.67***
6-move	0.49	1.63	0.09	5.60***
ITT	0.03	1.03	0.00	17.10***

Note. *$p<0.05$. **$p<0.01$. ***$p<0.001$.

PCT = Predicted Item Completion Time.

ITT = Initial thinking time.

Table 23

Random effects structure of children's item completion time (sec).

	Variance	SD	p
Participant	0.02	0.13	N/A
Item	0.02	0.15	0.00***
Modality	0.00	0.00	0.00***

Residual	0.14	0.38	N/A

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Modality contributed significantly to the amount of time children took to complete trials, with children taking significantly less time to complete trials on the keyboard, $t = -4.47$, $p < 0.001$. Optimal number of moves also had a significant effect on children's trial completions times. Children took significantly longer to complete 4-move trials ($t = 2.82$, $p < 0.05$), 5-move trials ($t = 5.67$, $p < 0.001$) and 6-move trials ($t = 5.60$, $p < 0.001$) compared to 3-move trials. Overall, 5-move trials took the longest to complete with an estimated 1.65s increase in time relative to 3-move trials, followed by 6-move trials (1.63s) and 4-move trials (1.27s). The amount of time children spent playing video games per week also caused a significant reduction in item completion time with children whose parents reported their child averaging 1-5 hrs/week gameplay taking longer ($t = -2.87$, $p < 0.05$) to children spending 6-10 hrs/week ($t = -2.88$, $p < 0.05$). Note here however, that only one child was reported to play for between 6-10 hours. The findings indicate that children playing for between 1-6 hours a week ($n=9$) were faster than children who were reported not to play at all. Children's initial thinking time had a significant bearing on their item completion time, $t = 17.10$, $p < 0.001$, whereby children who took longer to plan their first move also took longer to complete trials.

Move efficiency analysis

Following the same logic as the previous experiment, I standardised the number of moves executed for each level of Optimal number of moves by dividing the number of moves executed by the optimal number of moves. This calculation generated a movement efficiency score for each level of optimal number of moves.

Table 24

Mean move efficiency, frequency and percentage (%) of optimal completions.

	Move efficiency	Optimal completions	Percent Optimal (%)
Modality			

Floor mat	1.16	188	65.28%
Keyboard	1.20	181	60.13%
Optimal number of moves			
3-move	1.18	110	73.33%
4-move	1.17	95	66.90%
5-move	1.18	78	55.71%
6-move	1.17	84	65.63%

Note. Move count excludes trials that had to be Restarted or Skipped.

Table 25

Best predictor model for children's movement efficiency

	β	PME	SE β	t-value
Intercept	1.18	-3.25	0.02	58.52
4-move	-0.01	-0.99	0.03	-0.23
5-move	0.00	-1.00	0.03	0.07
6-move	-0.00	-1.00	0.03	-0.05

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.
PME=Predicted move efficiency.

Linear mixed effects analysis revealed that there no factor significantly contributed to the move efficiency of participants.

Table 26

Random effects structure of children's move efficiency.

	Variance	SD	*p*
Participant	0.00	0.00	N/A

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

First attempt success analysis

Next in the analysis I examined the number of suboptimal and optimal completions from children's first attempt. To analyse the different problem strategies children adopted for the task, here I conducted a series of logistic regression (again using the lme4 package), using the binary outcome of optimal number of moves to completion and sub-optimal number of moves to completion as the dependent variable. An optimal completion was coded as '1', and a suboptimal completion as '0'.

To begin the modelling process the random effect of Participant and fixed effect of Optimal number of moves entered the model. Following the stepwise process of the previous analysis, identifying first random variance, fixed effects and hypothesis effects revealed no significant contributors to the variance in the model. So, the final model consisted of the baseline model.

```
Model (1) = First attempt success ~ 1 + Optimal number
of moves + (1|Participant), family = binomial
```

The results of the binary logistic regression are reported below.

Table 27

Best predictor model for children's first attempt success.

	β	Prob. FAC	SE β	z-value
Intercept	0.96	2.61	0.18	0.00***
4-move	-0.42	0.66	0.25	0.49
5-move	-0.78	0.46	0.25	0.00**
6-move	-0.57	0.57	0.25	0.02*

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Prob. FAC = Probability of First Attempt Completion.

Table 28

Random effects structure of children's first attempt success.

	Variance	SD	p
Participant	0.00	0.00	N/A

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The probability of children achieving the optimal number of moves on the first attempt was significantly less on 5-move items ($z = 0.00$, $p < 0.001$), with a probability of .46 relative to 3-move trials. Children were also significantly less likely to complete trials successfully on the first attempt on 6-move items relative to 3-move items ($z = 0.02$, $p < 0.05$) with a comparative probability of .57.

Invalid moves

I then moved on to investigate the number of invalid moves children executed in the task. For this analysis, I included trials that were either restarted or resulted in an item being skipped due to the frequency of invalid moves on these occasions. I noted that cases where children could no longer move the frog did not necessarily stop them from attempting to. So, it was of interest to examine how use of each interface affected children's propensity to execute an invalid move. To recap, invalid moves were moves that were prohibited by the games design, such as trying to hop into the water or diagonally, onto an inaccessible lily pad. I first examined the distribution of this data to determine if it had a Gaussian distribution. Figure 23 demonstrates that this data was positively skewed.
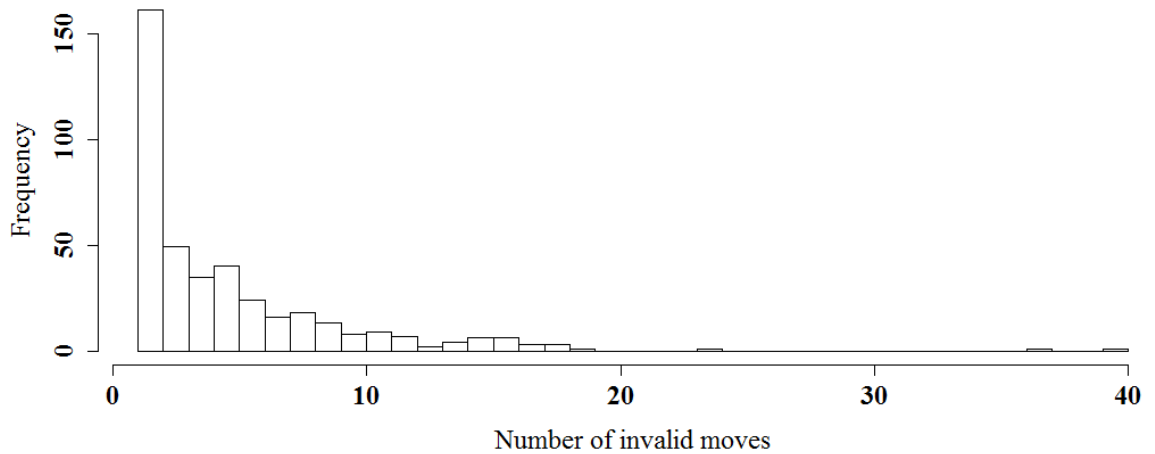
Figure 23. Histogram of children's invalid moves.

For further clarification of the data's distribution I examined the number of invalid moves minimum, maximum, and median. Although the minimum for this data was particularly compelling (zero for each factor investigated), the maximum and median provide an indication of how each factor contributed to the number of invalid moves made by children.

Table 29

Median, maximum and sum of children's invalid moves.

	Median	Max	Sum
Modality			
Floor mat	1	40	999
Keyboard	1	37	1176
Optimal number of moves			
3-move	0	18	131
4-move	2	19	529
5-move	3	40	919
6-move	2	37	596
Modality × Optimal number of moves			
Floor mat			
3-move	0	18	92
4-move	1	18	277
5-move	2	40	408
6-move	2	16	272
Keyboard			
3-move	0	12	39
4-move	2	19	302
5-move	3	24	511
6-move	2	37	324

[6]

Analysis of Invalid Moves

To examine the factors that contributed to children's invalid moves a LMEM was applied to the data using a Poisson distribution and the glmer package. A Poisson regression was chosen as the data was count in nature, and distributed non-linearly. A Poisson regression also accounts for observations of the value 0, by converting all observations into a positive value.

---

[6] Note that the minimum was omitted as each variable produced a value of 0.

The modelling procedure follows those detailed previously, identifying first the models random effect structure, fixed effects, and finishing with an examination of the hypothesis variables. The fixed effects for this model was Optimal number of moves, as I expected children to execute more invalid moves the deeper the problem space. The hypothesis variables in this analysis were Modality, Modality $\times$ Optimal number of moves, and initial thinking time.

Examination of the random variance in the model indicated that both Item and Modality accounted for a significant portion. Therefore, the baseline model took the form:

```
Model (1) = Invalid moves ~ 1 + Optimal number of moves
+ (1|Participant) + (1|Item) + (1|Modality), family =
poisson
```

I then entered each subtest and overall score from the BADS-C, WAIS-II, and Research Questionnaire on the Impact of Technology on Children Questionnaire individually, and tested their contribution to the models variance via ANOVA. From this series of analysis children's performance on the Block Design Subtest of the WAIS-II provide to be a significant contributor and so entered the model ($p < 0.001$).

```
Model (2) =   = Invalid moves ~ 1 + Optimal number of
moves + Block Design + (1|Participant) + (1|Item) +
(1|Modality), family = poisson
```

I then entered each hypothesis variable in to the model, testing each with an ANOVA. This step-wise process revealed that the interaction Modality $\times$ Optimal number of moves contributed significantly to the variance in the model ($p < 0.001$). No other hypothesis variables explained a significant portion of the models variance, and so, the final model took the following composition:

```
Model (3) =   = Invalid moves ~ 1 + Optimal number of
moves + Block Design + Modality * Optimal number of
```

120

```
moves + (1|Participant) + (1|Item) + (1|Modality),
family = poisson
```

The results of LMEM with a Poisson distribution of children's invalid moves are presented in table 30.

Table 30

Best predictor model for children's invalid moves.

	β	SE β	z-value
Intercept	0.38	0.21	1.81
4-move	0.84	0.15	5.53***
5-move	1.35	0.15	9.23***
6-move	1.09	0.15	7.20***
Block design	-0.03	0.01	-3.56***
Keyboard	-0.72	0.19	-3.82***
4-move * Keyboard	0.95	0.21	4.56***
5-move * Keyboard	0.89	0.20	4.43***
6-move * Keyboard	0.88	0.21	4.24***

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Table 31

Random effects structure of children's invalid moves.

	Variance	SD	*p*
Participant	0.16	0.40	N/A
Item	0.02	0.13	0.00***
Modality	0.00	0.00	0.00**

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 30 demonstrates that children executed more invalid moves on 4-move items ($z = 5.53$, $p < 0.001$), 5-move items ($z = 9.23$, $p < 0.001$), and 6-move items ($z = 7.20$, $p < 0.001$), relative to 3-move trials. Children's performance on the Block design significantly contributed to the number of invalid moves they executed, whereby higher

scores on this subtest were related to fewer invalid moves $z = -3.56$, $p < 0.001$. Children made significantly more invalid moves on the keyboard relative to the floor mat ($z = -3.82$, $p < 0.01$). Moreover, children executed more invalid moves on 4-move ($z = 4.56$, $p < 0.001$), 5-move ($z = 4.43$, $p < 0.001$), and 6-move ($z = 4.24$, $p < 0.001$) items while using the keyboard relative to the floor mat.

DISCUSSION

The following experiment examined children's planning using an updated version of the task described in the previous chapter. Changes were made to the methodology to provide a closer analysis of the effect of embodiment on children's task performance. These changes included altering the visual perspective of the floor mat condition, whereby children could view the display and the floor mat simultaneously, only children in P3 were included in the sample in order to focus on the effect of embodiment and not age related differences in performance, additional levels of optimal number of moves were added to provide a more robust means to test this task parameter, and interaction on the floor mat was video-recorded to generate a better understanding of children's actions and if action congruency was achieved.

In the previous chapter, it was unclear whether children achieved 'action congruency' as there are a variety of movements that can be used to move across the padded buttons of the floor mat. By video-recording children's task performance I could generate a better idea of how children used this technology, and, whether they could be said to imitate the actions of the virtual character (e.g. hop like a frog). On several occasions children chose to jump between the directional keys on the floor mat in a frog like manner, by hopping with both feet from one button to another. However, this type of action was executed by only 3 out of the 20 children. And, out of these 3 children, each gradually moved away from frog hopping to adopt a more economic form of movement, by stepping rather than jumping between the directional buttons. The qualitative analysis of children's movement revealed that stepping onto each key with one foot, while keeping the other foot in the central neutral button to be the most widely and frequently adopted strategy. Ideally, every child would have adopted the same movement technique, however, while using the mat children were free to move in the way they felt most comfortable. The children who did frog hop did not maintain this technique, suggesting that children preferred to move their bodies in an economic manner. That is, children

preferred not to expend too much energy while completing the task on the mat. Future research in this area should consider this finding, as technologies for children are designed by adults, designers must consider the physical capacities of their target age group. I had hope that children would jump between the different directional keys of the floor mat, imitating the action of the onscreen character, but instead children preferred to execute conservative movements. The most important message from the qualitative analysis was that while using a floor mat, children regularly step between the directional keys, and so in the last experiment I leveraged this information to create a new embodied task involving this action.

Effects of changing experimental setup

The results from the quantitative analysis of children's performance demonstrated that changes to the experiment's format could have a significant impact on the strategies adopted by children. In this experiment, children spent longer planning their route (as evidenced by increased initial thinking time), and took longer to complete trials while using the floor mat. This finding contrasts with those of the previous experiment whereby children demonstrated a more careful and deliberated approach while using the keyboard. Moreover, analysis of the number of invalid moves children executed showed that children generated fewer invalid moves on the floor mat. Together, these findings suggest that changing the visual layout of the task greatly assisted children's planning performance. Removing the need to constantly switch their visual attention between the floor and a desk monitor allowed children to spend more time analysing the problem and formulate a sequence of actions to solve the problem. Lindgren and Johnson-Glenberg (2015) have used interactive floor displays to teach children about how gravitational forces affect the flight path of an asteroid. They found that children's learning benefitted from displaying the information on the floor and allowing each child to be a protagonist in the virtual environment (e.g. assume the role of the asteroid). Hence, the user's visual perspective is crucial in the assessment of embodied cognition and technology. As we move into an age where computing is becoming less physical and more virtual (for example, the Microsoft HoloLens) the learning environments we create for children using these technologies must consider the visual perspective children will assume when completing task. Technologies that allow children to process content and move their body without having to visually inspect their bodies positon are better placed to teach children.

A positive trend for embodiment

The goal of the experiment was to demonstrate that use of the floor mat would produce better planning performance. This effect would be represented by the significant contribution of the floor mat to children's number of moves and optimal completions. And, although there was a trend in the descriptive statistics to suggest children complete more trials correctly and executed less moves on the floor mat, this effect was not significant. This lack of effect however represents an important change in performance pattern from the previous experiment. In experiment 1, children completed trials in less moves while using the keyboard. The present experiment reversed this effect, but did not reach statistical significance. There are several possible methodological reasons for this improvement. Most importantly, children no longer had to formulate a sequence of moves to execute in a stagnant manner. Allowing children to view the floor mat and the display simultaneously allowed them to generate strategies without the intermission of looking at another visual plane. Furthermore, this change represented a reduction in working memory, as children could maintain their planned sequence of actions without the need to switch attention to the location of their feet. Thus, the parity achieved between each device demonstrates that planning is affected by the working memory demands of the task.

Additionally, the data of invalid moves indicates that children were more cautious and deliberated in their approach while using this device relative to the keyboard interface. In the current experiment, children executed more invalid moves using the keyboard while completing 4-, 5- and 6-move problems. This result marks a significant shift to children's planning performance, as in experiment 1 children were less careful with their move execution while using the floor mat: floor mat = 645, keyboard = 290. Given that experiment 1 showed that the motor component to response generation does not necessarily mediate children's planning approach, here I argue that the finding supports a significant to change children's conceptualisation of the task. That is, the modifications made to the task encouraged children to pay closer attention to the planning elements of the task, rather than act of moving their bodies. By developing a setup whereby children could visually process the task elements and quickly generate a response without fear of losing their balance or stepping on an incorrect pad, children could focus on planning their route rather than the challenges of using the technology.

Videogame experience and performance

A consideration from the previous experiment was that perhaps children's performance on the task was being mediated by their prior experience with computer or video games. Here, parents filled out a questionnaire related to their child's use of technology, and I examined the implications of three items: Hours/week child watches TV/DVDs; Hours/week play video games; Hours/week play portable video games. Interestingly, children whose parents reported that they played 1-5 hours of video games per week ($n = 10$) were faster to complete trials to children who did not play video games ($n = 9$). While the format of the task resembled a videogame, it was developed from the literature of EF. So, these findings in some way demonstrate that video games can improve certain aspects of EF in children as young as 7 years. In the present experiment, children who play video games between 1-5 hours/week were faster to correctly complete trials. Research of video games has previously demonstrated that expert 'gamers' show enhancements visual processing skills, such as changes to moving targets in an array (Green & Bavelier, 2003). However, to my knowledge, this is the first experiment to demonstrate that videogame experience in young children can have a positive effect on their EF. Video games are intrinsically challenging, and often require the player to plan to progress through the game. In children's videogame Banjo and Kazooie, the player navigates the protagonists through a series of puzzle based levels. Each puzzle forces the player to consider the skillset of each protagonist to be completed successfully. Banjo can transform into a level specific creature for certain tasks, whereas Kazooie can run up steep ground. Completing a level successfully in the game requires planning, as children must consider the elements of the problem they face in relation to the abilities of each protagonist. There are many games on the market like Banjo Kazooie designed to challenge children's problem solving. It is not surprising therefore, that repeated engagement with this media improves the speed that children process information from a task.

Perceptual reasoning and task performance

An added facet of this investigation was to study how performance on the planning task mapped on to other cognitive assessments. To do so, children completed an IQ assessment (WAIS-II), and an EF battery (BADS-C). Conceptually, the task was developed to assess the EF planning. However, the analysis revealed that the two perceptual reasoning elements of the WAIS-II contributed to children's performance, more so than the subtests from the BADS-C. Specifically, children's scores on the Matrix

Reasoning subtest predicted the length of time the planned their first move, and Block Design scores related to the number of invalid moves children executed. Taken together, these results are noncontroversial, as the planning task detailed in this experiment requires visual perceptual processing. In the Matrix reasoning subtest of the WAIS-II success on each trial is determined by children's cognitive construction of a pattern. Selecting the item that continues that pattern to the one shown on the page takes careful consideration of the patterns composition. The same type of processing is required when planning the route on Slippy's adventure. First, the child must view the problem and mental construct a sequence of moves. In the Block Design subtest, children had to construct a pattern from a set of blocks, thereby allowing them to hypothesis test and adopt a trial-and-error strategy. The number of invalid moves children executed in Slippy's Adventure also demonstrates children's proclivity to adopt a trial-and-error approach. The indication that children who performed well on Block Design made less invalid moves on the task suggests that the ability to physically construct a solution to a puzzle from blocks relates to children's ability to mentally deconstruct a problem. Completing trials in Block Design requires consideration of the blocks physical composition, and how this composition could be arranged to create a certain pattern. The more accurate the matching between the block composition and the final pattern, the less errors will be incurred. The same could be said for Slippy's Adventure, whereby the better children are at deconstructing the problem into its constituent moves, the less invalid movements they are likely to execute. So, the findings indicate that Slippy's Adventure, although conceived as a planning task, also requires a degree of perceptual reasoning.

CONCLUSION

The present experiment used the same planning task in the previous chapter, with modifications made to both the format and the methodology. It appears that children benefitted from changing the location of the display, as it reduced the working memory demands of the task by allowing children to process both the configuration of the puzzle on screen, and the location of their feet. Children's videogame expertise also played an important role in their planning performance, a finding that demonstrates the power of this median to train certain cognitive skills in children. Children's perceptual reasoning explained some aspects of variance in the data, as the Block Design and Matrix Reasoning subtests share the feature of problem-deconstruction. Regarding embodiment however, a closer look at the type of movements children executed on the floor mat indicate that this

device is better at facilitating stepping as opposed to jumping. Although children's performance between the floor and the keyboard were similar in terms of the number of optimal completions the qualitative analysis indicate that this effect was not related to action congruency. In my last experiment, I considered the findings from the empirical work documented this far to create a floor mat task with a greater sense of embodiment, while retaining the core principles of an EF task.

CHAPTER 5 – EXPERIMENT 3

Having demonstrated that the effects of embodied cognition on children's planning represent a small trend toward preference for the floor mat, I changed the executive skill of interest. Planning is a high level cognitive ability that is sub-served by other EF skills (Miyake et al., 2000). Thus, a more finessed approach to examining the effect of embodiment on children's EF would be to examine their performance using the same setup, but on a task, that tested a foundational executive skill.

From planning to inhibition

Effective planning requires a certain level of restraint, focus, and avoidance of distraction (Anzai & Simon, 1979). In Slippy's adventure this ability to stop and plan was evidenced by the range of initial thinking times, as some children stopped to check their progress, and on occasion trace a path with their finger to formulate a plan of action. Stopping to inform decision making and disregarding habituated behaviours are the behaviours that are at the core of the EF inhibition (Shallice & Norman, 1980), and like planning, could be considered embodied given that it is skill developed from experience. In their model, Shallice and Norman (1980) stipulate that the extent that an individual inhibits their behaviour, such as saying something out of turn, is determined by the familiarity of the situation. In this example, the rules of turn taking are built from with conversations, and a growing recognition that there is a social etiquette to abide to.

Developmental significance of inhibition

With respect to development, inhibition is important as it provides a platform for children to go beyond sporadic, fleeting decision making to a more deliberate and careful approach. For this reason, it is proposed that children's inhibition at pre-school predicts their academic achievements in the years to come (Bull & Scherif, 2001). So, understanding the process by which this ability matures is an important one. The embodied cognition perspective suggests that children's sensorimotor experience in their environment, and growing understanding of the bodies capabilities mediates this development in some way (Glenberg, 2010). Perhaps, it is the development of controlled, coordinated movement that fosters a cognitively careful approach too. Thus, in the following experiment I asked children to complete a test of inhibition using the same

modalities from the previous experiments. My observations and findings informed the design of this final experiment, to provide the best possible assessment of inhibition and embodied cognition. Importantly, children's interactions with the floor mar provided a framework, to develop a task that children felt a part of, and experience a movement that was contextually relevant to the task.

Facilitating children's floor mat interactions

My investigations indicated that children were less likely to hop on the floor mat, and prefeed to step between the keys. Taking this into consideration I chose to develop a flanker task whereby the embodied condition would facilitate this action. This modified version of the flanker task set up a premise whereby children were a hero protagonist, responsible for saving humans from an alien invasion. The only way this invasion could be stopped was if the aliens that landed were squashed. Thus, the focus of the experiment shifted away from an action that was somewhat supported (e.g. frog hopping), to one that occurred by proxy, without the need for motivational or situational cues to prompt a specific response (e.g. telling the children to assume the role of the frog). In this flanker task, children responded to the target stimulus by stepping on the left and right arrows, matching the actual action of 'squashing' in the real world. Again, the task resembled a video game in the sense that the stimuli used related to children's interaction with technology. In this case, the aliens provided a visual representation of traditional assessment materials, in an environment where children were active protagonists, digitally 'squashing' their foes, rather than passive observers.

Providing context

The format for the flanker task described later took inspiration from a modified of the version flanker task with a similar setup. In Rueda and colleagues (2012) task children responded to two different stimuli, fish and arrows (for more details of Rueda et al. (2004) please refer Chapter 2: Inhibition). Importantly, the authors found that the type of stimulus can have a significant impact on children's performance in the flanker task, namely, that providing a story and related images improves children's ability to avoid visual interference, and thus, inhibit visual distractions. I followed this approach as including both story like and traditional target stimulus would provide the opportunity to determine how context, and embodiment affect inhibition. In the following task, children saw both

the traditional flanker arrow stimuli (angled brackets) and Alien stimuli. Aliens were chosen because UK children's preference for games that include an element of fantasy (Livingstone, Marsh, Plowman, Ottovordemgentschenfelde, & Fletcher-Watson, 2014). Moreover, films that include Aliens/Monsters are among the most popular for children, including titles such as Wall-E, Monsters Inc., and Monsters University (Streib, Ayala, & Wixted, 2016).

Effects of embodiment

Response modality was modified to include an embodied form of interaction as well as a traditional response modality and task presentation. Moreover, I combined the variables of modality and stimulus type I created 4 versions of the task to be counterbalanced across two experimental sessions: Alien stimuli and Floor Mat; Alien stimuli and Numberpad; Arrow stimuli and Floor Mat; Arrow stimuli and Numberpad. Embodiment could be studied by investigating the difference in performance between each of these conditions as each mapped onto concept with varying degree depending on the alignment between response modality, story, and stimuli. The story facilitated a stepping action with Alien stimuli. So, the most embodied condition was proposed to be the Alien Stimuli and Floor mat version of the task. The least embodied condition was the version of the task that did not fit either the story or the response modality; the Arrow stimuli and Numberpad condition. In short, I predicted that children would feel a greater sense of embodiment while squashing the target Alien stimuli comparatively to the condition whereby children responded to angled brackets by pressing a matching directional button on a numberpad. This greater correspondence between the movement children make and the context of that movement (i.e. the story) would results in a decline in the flanker effect; a decrease in processing time of incongruent stimuli and increased success rate (Eriksen & Schultz, 1979). Given the importance of speed and accuracy in this experiment I also included a measure of children fine and gross motor control.

Motor control and coordination

As previously stated, fine and gross motor control have shown to mediate specific elements of EF to date. Rigoli and colleagues (2013) demonstrated that fine motor control predicted children's working memory ability between the ages of 5 and 11 years. Evidence of this link has also been demonstrated in sample with a developmental

disorder. Using a modified Go/No-go task Rahimi-Golkhandan et al. (2016) showed that children with DCD are less able to inhibit response execution relative to typically developing children. DCD, formerly known as dyspraxia, is a disorder marked by poor balance, fine motor control, and clumsiness (APA, 2013). Thus, the inability to effectively manage and coordinate body movement is associated with deficiencies in inhibitory processes. In the present task, this association would present itself as a reduction in flanker errors and increased speed of response for those children who show strong balance and coordination. It is possible that the results I have gathered to this point reflect individual differences in children's motor coordination rather than embodiment. This issue is especially pertinent given the literature suggesting that executive abilities function as part of a neural network including the cerebellum (Brunamonti et al., 214; Diamond, 2000; Strick, Dum, & Fiez, 2009), the region proposed to be responsible for timing and movement execution. So, here I included a parent report measure of children's motor control within the experimental design.

Hypotheses

My priority was to determine the effect of the embodied condition (Aliens, Floor mat) relative to the less embodied condition (Arrows, Numberpad). I hypothesized that in the embodied condition, children's response times would be relatively faster, and that they would produce more correct responses. Further, given the indication that making a task more game-like in presentation can improve performance, here I expected children to experience less interference when responding to alien stimuli, as opposed to arrow stimuli. Finally, I also predicted that motor coordination would mediate flanker task performance, such that more coordinated children would perform better on the flanker task.

METHOD

Participants

Thirty typically developing children aged 7 years (M=7.44, SD=3.87), of which 13 were female. Participants were recruited via post; parents were sent an information letter and a consent form detailing the aims of the study and requesting permission for their child's participation. None of the children had a diagnosis of a developmental condition. The study was approved by Heriot-Watt University's Ethics committee, approval number: 2015:43.

Design

The study was a $2 \times 2 \times 3$ repeated measures design including the factors of modality (Floor mat, Numberpad) stimulus type (Alien, Arrow), and congruency (Neutral, Congruent, Incongruent). The dependent variables were the number of correct responses made by participants and their RT (ms).

Materials

BADS-C

Children completed the Behavioural Assessment for Dysexecutive Syndrome for Children (BADS-C; Emslie, Wilson, Burden, Nimmo-Smith, & Wilson, 2003), a battery intended for use with children 7+ years. The BADS-C comprises 6 EF tasks including Playing Cards, Water Test, Key Search, Zoo Map 1, Zoo Map 2, and the Six Parts test. Each task tests different EF skills (for more details see chapter 4: BADS-C). The scores from these tasks was considered independently in the analysis, to determine how each subtest related to performance on the flanker task.

DQDQ'07

The Developmental Coordination Disorder Questionnaire 2007 (B. N. Wilson, Kaplan, Crawford, & Roberts, 2009) is a 15 items parent report measure of children's motor coordination. Answers are provided along a 5-point scale: 1 Not at all like your child; 2 A bit like your child; 3 Moderately like your child; 4 Quite a bit like your child;

5 Extremely like your child. Parents are asked to complete the questionnaire by drawing comparisons with other children who are the same age the their own. The questionnaire derives three scores for children's Control During Movement (e.g. "You child throws *a ball* in a controlled and accurate fashion"), Fine Motor/ Hand writing (e.g. "Your child's printing or *writing* or drawing in class is *fast* enough to keep up with the rest of the children in the class") and General Coordination (e.g. "Your child is interested in and *likes* participating in *sports* or *active* games requiring good motor skill"). Each of these sections is also combined to provide an overall score for Motor Coordination. Control During Movement is scored out of 30, Fine Motor/ Handwriting is scored out of 20, and General Coordination is scored out of 25. Thus, the maximum score a child can obtain on the DCDQ is 75. Subtest and total score on the DCDQ were taken into consideration relative to children's performance on the Flanker task.

Flanker task

The Flanker task was presented to children on a 14" display monitor connected to a laptop computer. The task was run on PsychoPy (http://www.psychopy.org/) software.

Figure 25. Image of Floor mat modality setup.

<u>Modalities</u>

The floor mat is a padded mat with a marked 3 x 3 square grid. Each square in the grid includes an orthogonal direction key (i.e. UP, DOWN, LEFT and RIGHT). In the centre of the mat is a neutral starting square, where participants were asked to stand to begin each trial. The floor mat was interfaced with a Dell precision laptop via a gaming pad emulator; Joystick2keyboard (J2K; http://emulation-evolved.net/). The J2K emulator mapped the keyboard buttons to the floor mats buttons, thereby matching their button's function. For example, stepping on the left arrow on the floor mat when the Flanker target pointed to the left provided a correct response, as would pressing the LEFT arrow button on the computers keyboard.

Figure 26. Numberpad response modality with '4' and '6' keys overload with image of blue arrow.

The other response modality was a Logitech USB wired numberpad. To reduce the processing demands of the device the response keys – number 4 and 6 – were overlaid with an image of a blue arrow. Blue was chosen as it resembled both the colour of the target stimulus in the Alien flanker task, and matched the colour of the left and right response pads on the floor mat. While using the numberpad children sat on a comfortable chair and were instructed to use their thumbs of the corresponding hand (i.e. left button, left hand thumb) to make their response.

Procedure

Children were tested individually on school premises in a quiet room on three separate occasions a week apart. In the first session children completed the BADS-C. In the second and third session children played the flanker task using the floor mat one week and the numberpad the other. The order of modality (floor mat, numberpad) was counterbalanced. The temporal elements for this experiment were taken from Rueda et al (2004). In the flanker task children viewed the screen at 55cm. To begin, children were shown a fixation cross in the centre of the screen for 150ms. Then a cue – an asterisk – was presented in the target location for 450ms. The target stimuli were then presented >5000ms. Children could respond during the target onset. If the target display finished before a response was made, a blank screen was shown, during which children had to respond to move onto the next trial. Response feedback lasted for 1500ms followed by the fixation cross to begin the next trial. To begin, children were given 8 practice trials, which included at least one trial of the level of congruency (Neutral, Congruent, Incongruent). After the practice, children completed two blocks of 48 trials, with a short break in between. Each block contained either the Alien or the Arrow task. The order of stimulus presentation was also counterbalanced, creating four ordered versions of the task. The feedback between the Alien and Arrow version of the task differed and are described below.

Alien Invasion Game
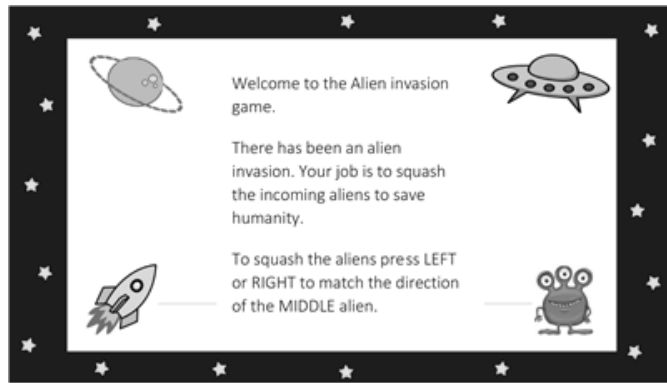
Figure 27. Opening Screen for the Alien version of the flanker task.

In the Alien version of the task, I read instructions stating that there had been an Alien invasion, and that it was up to the participant to stop the invasion to save humanity. To stop the invasion, children were instructed to 'squash' the Aliens by stepping/pressing (depending on the modality) on the left or right directional button to match the direction of the middle Alien. Children were also informed that sometimes several Aliens would appear at once, and on these occasions, to respond to the middle Alien. After reading aloud the instructions I double checked that children knew what was expected of them, and asked them to read out the onscreen instructions. These instructions echoed the rules and aims provided in the written instructions read initially. Children then completed the practice trials. The feedback for correct responses in the Alien Flanker task was designed to create a greater sense of embodiment. On successful trials an animated foot appeared at the top-centre of the screen, then moved down toward the target stimulus (see figure 29). Upon contact with the target stimulus a splat image appeared accompanied by a splat sound bite. Correct feedback lasted for 1500ms. Thus, while using the floor mat children's actions of stepping on the mat was matched by an onscreen squashing animation. Incorrect feedback was a low C tone beep that lasted for 1500ms. If participants attempted to squash an Alien before the onset of the target stimulus the following sentence was displayed in the centre of the screen for 5000ms, "Please wait until the Aliens have landed before you try to stop the invasion". This protocol was implemented to stop children from repeatedly stepping onto the floor mat, and to attend to the task.

Arrow Game
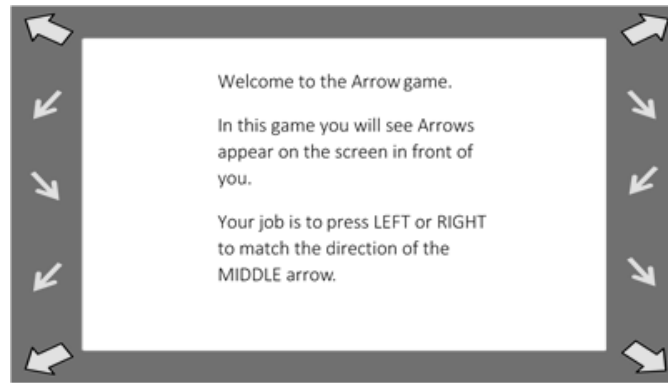
Figure 28. Opening Screen for the Arrow version of the flanker task.

The Arrow game was the same as the Alien except in two respects: the stimuli and the feedback. In the Arrow game the target stimuli were angled brackets pointing left or right. Both sets of stimuli had pointed edges, and were arrow like in shape to guide participants left/right decision making. The instructions for the Arrow game differed slightly to the Alien version of the task in that there was no story to the Arrow game. Children were told that they would see arrows appear on the screen and to press the button that matched the direction of the middle Arrow. As above, participants were also informed that sometimes they would see several arrows on the screen at once, and to respond to the middle Arrow on these occasions. Feedback in the Arrow game differed to the Alien game in terms of both the correct and incorrect feedback received. For correct feedback, the word 'Correct' appeared in the centre of the display accompanied by a cheering "Hooray" auditory file lasting 1500ms. For incorrect feedback participants saw the word 'Incorrect' appear in the centre of the screen accompanied by a low C tone beep lasting 1500ms. If participants attempted to respond to an arrow before the onset of the target stimulus the following sentence was displayed in the centre of the screen for 5000ms, "Please wait until the Arrows have appeared before you try to match their direction". For a visual representation of the flanker conditions by modality and stimulus type see Appendix D.
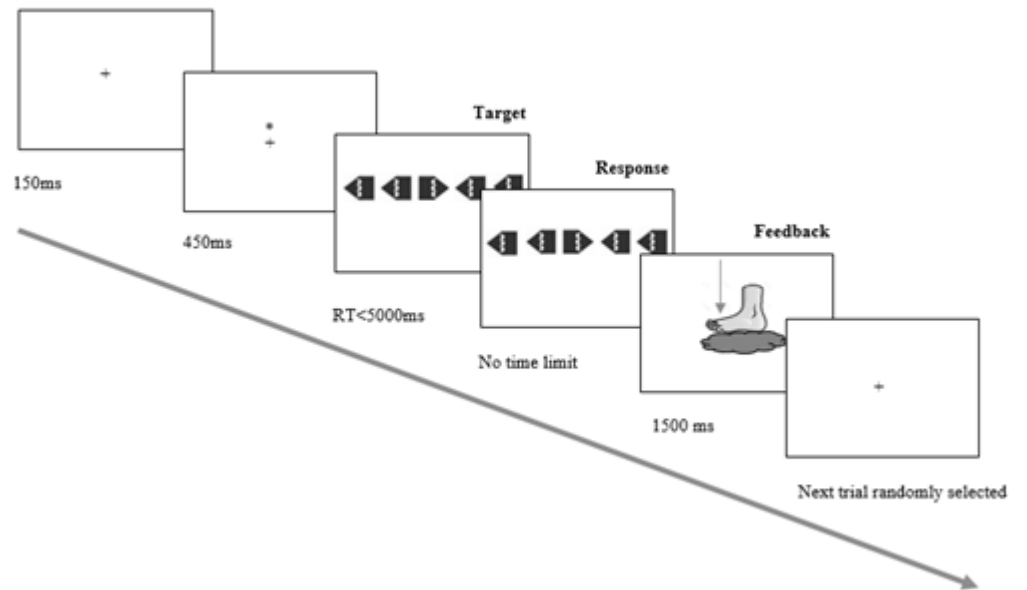
Figure 29. Alien flanker task procedure.

RESULTS

Modelling task flanker data

To investigate the parameters that significantly contributed to variance in children's response time (ms) LMEM was conducted in R using the lme4 package (Bates et al., 2014). Correct responses were of primary interest as this analysis was not concerned with accuracy, but effective processing time. The data pertaining to Neutral items was omitted for two reasons. First, these stimuli were not of theoretical relevance to the experiment as they did not include flanking stimuli that could potentially interfere with the participant's decision making. Secondly, lack of variance in both the Neutral and Congruent conditions prohibited model convergence. Table 34 (see below) indicates that children made very few errors on both Neutral (1.21% error) and Congruent (1.14% error) items. The procedure for identifying these parameters followed the analysis protocol detailed in the previous chapters; identify the random effects structure, followed by fixed effects, followed by testing the contribution of the hypothesis variables.

Random effects

In this experiment the random effects considered were Participant (i.e. baseline model), Item, Item Direction (e.g. left or right), and Modality. Participant was selected as a random effect as children were recruited from a random sample. Item was considered a random effect as children may have been better able to process Alien or Arrow, or a group of stimuli over individually presented stimuli. Item Direction was also considered as some children may have been more adept at responding to stimuli based on the direction it was presented. Modality was selected given that children may have shown preference for one modality over another.

Fixed effects

Fixed effects for this analysis were Congruency (Congruent and Incongruent), as I expected that children would take longer and demonstrate more performance errors in the incongruent condition comparatively to Congruent and Neutral trials. In the analysis of RT, I considered Modality as a fixed effect, as I expected RT on the floor mat to be significantly elevated relative to the keyboard. That is, children would take longer to response using their feet to pressing buttons on the numberpad with their thumbs.

Additionally, each of the subtest scores from the BADS-C and DCDQ'07 were entered individually as fixed effects and their contribution to the models variance assessed with ANOVA.

Hypothesis variables: correct response time

The hypothesis variables for this experiment were the interaction between Modality × Congruency, Stimulus type (Alien, Arrow), and Modality × Stimulus Type. The interaction between Modality and Congruency was considered as, if an effect of action congruency were present, it would represent a relative reduction in the difference between the processing times for congruent incongruent and items, based on the factor of Modality. In other words, children's processing time between congruent and incongruent items would be closer on the floor mat (if an effect of action congruency took place) to the difference between congruent and incongruent items on the numberpad. Stimulus type was considered a hypothesis variable as, in addition to the effect of embodiment, the two stimuli forms allowed me to investigate the effect of gamification on performance. The Alien task was designed in such a way to mimic the format of a videogame, while the Arrow task presented stimuli in a traditional flanker task format. So, performance differences between each of these stimulus types would provide an indication if inhibition is mediated by gamification. And lastly, the interaction between Modality and Stimulus Type was considered as this provided another window into the effect of embodiment. The 'most' embodied form of the task were those sessions where children completed the task using the floor mat and responded to Alien stimuli. Therefore, it was interest to determine whether children performed better on this embodied task presentation compared to less embodied formats: Aliens and numberpad, Arrows and numberpad, Arrows and floor mat.

Hypothesis variables: response accuracy

Children's accuracy was also of interest. Each response they provided was coded in terms of its accuracy; 1 = Correct, 0 = Incorrect. As the data was binary in nature a binary logistic regression was chosen to determine the parameters that significantly contributed to success or failure in the response to Congruent or Incongruent stimuli.

The random, fixed and hypothesis parameters investigated in this analysis were the same as those stated above, with the additional consideration of Modality and Response Time (RT) as hypothesis variables. Modality was entered as a hypothesis variable in this analysis as the outcome variable was not related to time, and so would provide an indication of the effect of interacting with the floor mat or the numberpad on children's response accuracy. Entering RT as a hypothesis variable allowed me to examine the effect of time on children's accuracy, as previous literature demonstrates that longer RT are associated with an increase in error rate (C. W. Eriksen & Schultz, 1979).

Pre-processing flanker task data

First, the factors that contribute to the variance in response time (RT; ms) were investigated. The distribution the data RT was positively skewed and contained some outliers (see figure 31). There were occasions where children did not pay attention to the task, and on one occasion a participant requested a break.
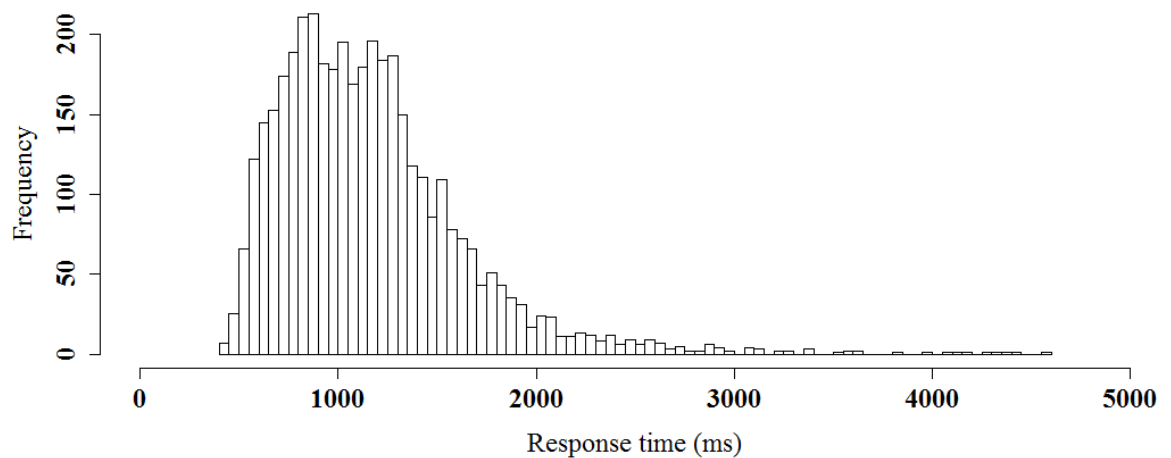
Figure 31. Histogram of correct response RT. Evident that the data is positively skewed, i.e. observations are clustered to the left.
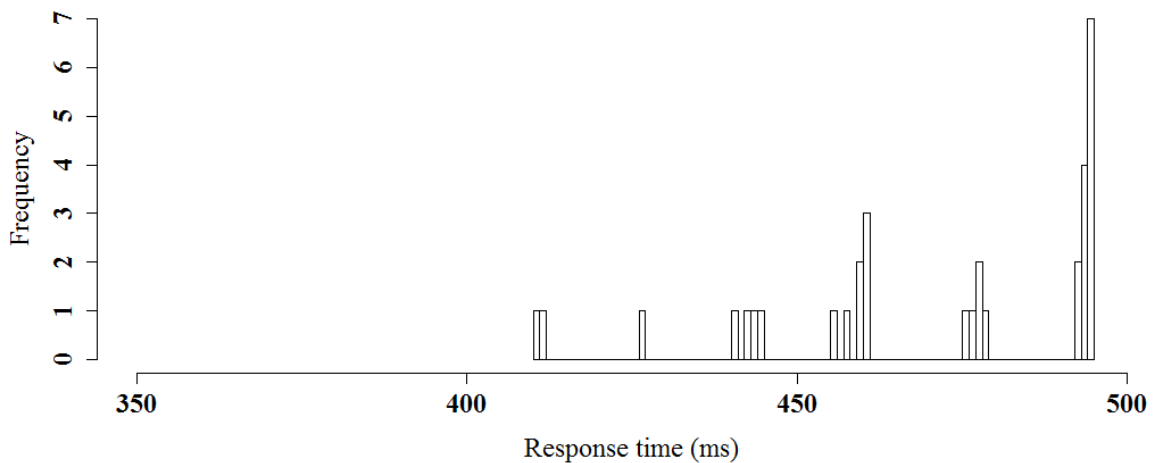
Figure 31. Histogram of responses less than 500ms.

A closer look at the responses that occurred between 0-500ms revealed a cluster of responses around the 400ms mark. This clustering indicated that several children can respond now. Responses that fell below 400ms likely reflected anomalies generated because of the measurement tool, and not participant efficiency. For example, while using the floor mat, participants had to keep their feet well within the centre square to avoid generating a response. Some children were better at this than others, but there were occasions where children made a response by having the edge of their foot overlap with one of the response squares. So, these accidental cases were removed. So, 400ms was chosen as the lower limit for response times. The upper limit of 5000ms was chosen as this corresponded to the target stimulus presentation time. Responses made after 5000ms may have been guessed or retrospective. Both processes do not relate to the process inhibition in the flanker task, where responses are made quickly to test the participants impulse control.

Response accuracy descriptive statistics

As can be seen children varied in terms of their baseline EF and Motor Coordination. In all the BADS-C subtests the samples score ranged from high- to low-competence.

Table 32

Means, range and standard deviations of the BADS-C and DCDQ'07.

Measure		Range	Mean	SD
BADS-C				
	Playing Cards	0-13	3.6	2.9
	Water Test	(-2)-10	3.8	3.01
	Key Search Test	(-1)-13	3.07	3.35
	Zoo Map 1	(-13)-8	-1.63	4.82
	Zoo Map 2	(-8)-8	4.47	4.88
	Six Parts Test	6-16	9.3	2.82
DCDQ'07				
	Control during movement	12-30	24.3	3.99
	Fine motor/ handwriting	7-20	16.1	3.21
	General Coordination	9-25	20.1	4.36
	Total	28-74	60.5	10.3

The playing cards test is marked per the number of errors made. So, in this test children's scores ranged from making 0 errors to 13 errors. The Water Test is marked by the number of steps in the problem correctly identified and acted upon. In this test, some children failed to identify any of these steps and were penalised for making incorrect actions (e.g. repeatedly using the wire to retrieve the cork) to those who identified all the correct steps to retrieve the cork. In the Key Search task children varied in their search strategy, with only a few utilising the desired search strategy. Children found both elements of the Zoo Map test challenging, particularly when requested in the open-ended version 1, where many broke the search rules provided. In the Six Part test, most of the children followed the rules and could complete an element from each of the six parts. Scores on the DCDQ'07 demonstrate the different motor coordination abilities of the sample, whereby a high indicates higher competency than a low score. To determine if these baseline measures could explain the variance in the data I ran correlations between each and the outcome variables of response accuracy and RT. None of the correlations yielded a significant relationship (See Appendix E).

To begin, I investigated the number of errors made by participants in each level of flanker congruency. By 'error' I refer to those occasions where children responded

incorrectly to the target stimuli in the flanker task; for example, if the target stimulus (e.g. an Alien in the middle of the screen) pointed to the left, and incorrect response would be to stand on the right directional button on the floor mat, or to press the right directional key on the numberpad. To assess the existence of the flanker effect on children's response accuracy within the sample I generated a summary table that considers congruency (Neutral, Congruent, Incongruent) and the number of errors made in each (see below).

Table 33

Frequency of correct and incorrect responses and error percentage (%) for each flanker condition.

	Correct	Incorrect	Total	Percentage Error
Neutral	1320	16	1336	1.21%
Congruent	1318	15	1333	1.14%
Incongruent	1125	196	1321	17.42%
Total	3763	227	3990	6.03%

Table 34

Frequency of correct and incorrect responses and error percentage (%) by flanker condition, stimulus, and modality.

Condition	Stimulus	Modality					
		Floor mat			Numberpad		
		Correct	Incorrect	Error	Correct	Incorrect	Error
Neutral	Alien	331	2	0.60%	328	7	2.13%
	Arrow	331	1	0.30%	330	6	1.82%
Congruent	Alien	332	2	0.60%	332	3	0.90%
	Arrow	325	7	2.15%	329	3	0.91%
Incongruent	Alien	284	46	16.20%	292	44	15.07%
	Arrow	269	56	20.82%	280	50	17.86%
Total		1872	114	6.09%	1891	113	5.98%

Table 35

Frequency of correct and incorrect responses and error (%) by embodiment.

| | Embodiment | | | | | |
| | Floor mat, Aliens | | | Numberpad, Arrows | | |
	Correct	Incorrect	% Error	Correct	Incorrect	% Error
Congruent	333	2	0.60%	329	3	0.91%
Incongruent	284	46	16.20%	280	50	17.86%
Total	948	50	5.27%	939	59	6.28%

Note. Data for 'Neutral' trials removed as this data was not used in the modelling process.

Analysis of response accuracy

Examination of the random effects structure of the data found no additional random factors, and so, only the random effect of Participant was included. So, the baseline model took the following composition:

```
Model (1) = Accuracy ~ 1 + Congruency + (1|participant),
family = binomial
```

I then entered each of the subtests from the BADS-C and the DCDQ'07 to determine whether EF or motor functioning explained a significant portion of the variance in children's accuracy. After adding each subtest individually and testing their contribution with ANOVA I found that children's score on the Playing Cards subtest of the BADS-C explained a significant amount of the variance in the model. So, children's score on the Playing Cards subtest of the BADS-C was added to the model.

```
Model (2) = Accuracy ~ 1 + Congruency + Playing Cards
+ (1|participant), family = binomial
```

As the fixed effect structure of the model had been finalised, I then moved on to entering each of the hypothesis variables. First I entered Modality into the model, to see if children's accuracy was mediated by the device they completed the task with.

```
Model (3) = Accuracy ~ 1 + Congruency + Playing Cards
+ Modality + (1|participant), family = binomial
```

An ANOVA between model 2 and 3 yielded a non-significant effect ($p = 0.45$). So, Modality was dropped from the model. In the fourth model, I considered the interaction Modality $\times$ Congruency.

```
Model (4) = Accuracy ~ 1 + Congruency + Playing Cards
+  Modality*Congruency  +  (1|participant),  family  =
binomial
```

An ANOVA comparison between model 3 and 4 found that the interaction Modality $\times$ Congruency did not contribute significantly to the variance in the model ($p = 0.22$), and so was omitted. I then entered the effect of Stimulus type to determine whether children were more accurate on the task depending on the presentation of the target stimuli (e.g. Aliens or Arrows).

```
Model (5) = Accuracy ~ 1 + Congruency + Playing Cards
+ Stimulus type + (1|participant), family = binomial
```

Comparing model 2 and 5 via ANOVA revealed that Stimulus type explained a significant portion of the variance in accuracy ($p < 0.05$), and so, Stimulus type was added to the model. Next, I examined the contribution of the interaction Modality $\times$ Stimulus type.

```
Model (6) = Accuracy ~ 1 + Congruency + Playing Cards
+    Stimulus    type    +    Modality*Stimulus
type(1|participant), family = binomial
```

Comparing the variance between model 5 and 6 with ANOVA revealed that the Modality $\times$ Stimulus type interaction did not significantly contribute to the models variance ($p = 0.74$). Finally, I added children's response time as a predictor variable.

```
Model (7) = Accuracy ~ 1 + Congruency + Playing Cards
+ Stimulus  type + Response  time + (1|participant),
family = binomial
```

Comparing the variance between model 5 and 7 yielded a non-significant effect ($p = 0.13$). So, RT was removed from the model. Model 5 was the optimal for predicting children's response accuracy. The results of the binary logistic regression with random effects are shown in table 39.

Table 39

Best predictor model for children's response accuracy.

	β	PCR	SE β	z-value
Intercept	5.91	N/A	0.46	12.93***
Arrows	-0.27	0.76	0.14	-1.99*
Playing Cards	-0.18	0.84	0.08	-2.09*
Incongruent	-2.79	0.06	0.22	12.72***

Note. * $p < 0.05$; ** $p < 0.01$. ***$p < 0.001$.

PCR = Probability of achieving a correct response.

Table 40

Random effects structure of children's response accuracy.

	Variance	SD	*p*
Participant	1.47	1.21	N/A

Note. * *p* < 0.05; ** *p* < 0.01; *** *p* < 0.001.

Binary logistic regression analyses revealed that children were significantly less likely to respond correctly to incongruent items z = -12.72, *p* <0.001. The analysis also revealed an effect of Stimulus Type whereby children were more likely to respond correctly to Alien stimuli comparatively to Arrow stimuli, z = 1.99, *p* < 0.05. Moreover, children's performance on the Playing Cards subtest of the BADS-C significantly predicted the probability of a child successfully responding to a target stimulus, *z* = -2.09, *p* < 0.05.

Analysis of response time (ms)

To model the response time data more effectively, a log transformation was performed. This provided a more Gaussian like distribution to model with (see figure 32). The histogram below represents the final distribution after having removed outliers, incorrect responses, and performed a log transformation on the data.
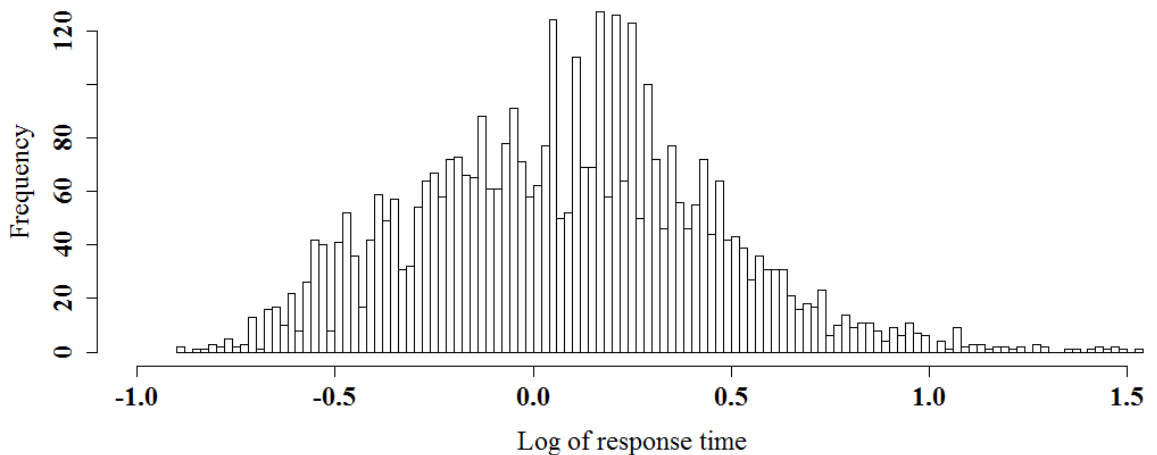
Figure 32. Histogram of log of RT for correct responses.

Having generated a more Gaussian like distribution I then began to investigate the effect that each hypothesis variable had on children's correct response RT. My hypothesis variables were Stimulus type (Alien, Arrow), Condition (Congruent, Incongruent, Neutral) and Modality (Floor mat, Numberpad).

Response time descriptive statistics

Below is a table of summary statistics for children's response time in the flanker task considering each hypothesis variable: Stimulus type, Condition, and Modality.

Table 36

Median and range of children's correct responses (ms).

	Min	Max	Median
<u>Stimulus Type</u>			
Alien	410	4411	1058
Arrow	443	4594	1094
<u>Condition</u>			
Neutral	410	4146	1008
Congruent	440	4161	1025
Incongruent	510	4594	1257
<u>Modality</u>			
Floor mat	494	4594	1259
Numberpad	410	4277	844

Congruent
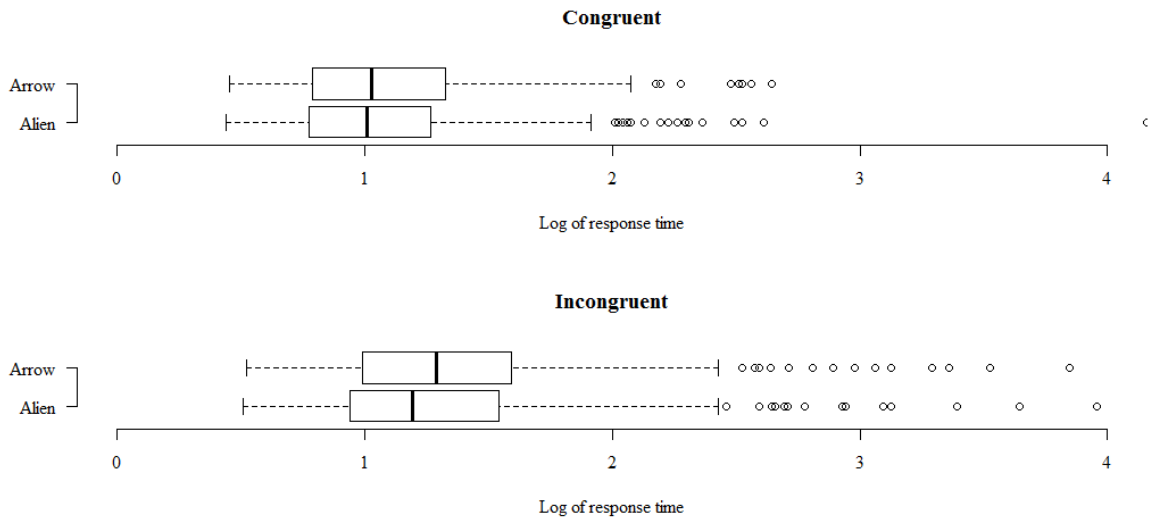
Incongruent

Figure 33. Log of response time for Congruent and Incongruent conditions modelled by stimulus type.

Modelling correct response time

An examination of the random effects structure of the model identified that Modality significantly contributed to the random variance in the model. Therefore, the baseline model for analysis took the following form:

```
Model (1) = log(Correct response time) ~ Modality +
Congruency + (1|Participant) + (1|Modality)
```

In the next phase, I added each subtest score from the BADS-C and DCDQ'07 into the model individually, and test their contribution to the models variance by ANOVA. None of these analyses were significant, indicating that subtests from each assessment tool did not map onto children's correct RT. So, I moved on to enter the hypothesis variables. First, I entered the interaction Modality × Congruency.

```
Model (2) = log(Correct response time) ~ Modality +
Congruency + Modality*Congruency + (1|Participant) +
(1|Modality)
```

150

Performing an ANOVA between model 1 and 2 found a significant difference, demonstrating that the Modality × Congruency explained a significant portion of the variance in correct response time, $p < 0.01$. Next, I entered the parameter Stimulus type to determine whether the presenting the flanker task in a game like manner significantly affected children's response time.

```
Model (3) = log(Correct response time) ~ Modality +
Congruency + Modality*Congruency + Stimulus type +
(1|Participant) + (1|Modality)
```

Comparing model 2 and 3 with an ANOVA found a significant effect, $p < 0.001$. Therefore, the effect of stimulus type was added to the model. Finally, I added the interaction Modality × Stimulus type, to determine if embodiment had a significant effect on children's RT.

```
Model (4) = log(Correct response time) ~ Modality +
Congruency + Modality*Congruency + Stimulus type +
Modality*Stimulus type + (1|Participant) + (1|Modality)
```

An ANOVA between model 3 and 4 yielded a significant effect, $p < 0.05$. So, the final regression model reported below refers to Model 4.

Results from the linear mixed effects modelling are provided in the table below.

Table 37

Best predictor model for children's response time (ms).

	β	Predicted RT	SE β	t-value
Intercept	0.17	1.19	0.03	5.11***
Incongruent	0.22	1.25	0.01	16.54***
Arrow	0.06	1.06	0.01	4.54***
Numberpad	-0.33	0.72	0.02	-20.70***
Numberpad * Incongruent	0.02	1.02	0.02	1.22
Numberpad * Arrow	-0.04	0.96	0.02	-1.97

Note. $* p < 0.05$; $** p < 0.01$. $***p < 0.001$.

Table 38

Random effects structure of children's response time.

	Variance	SD	*p*
Participant	0.03	0.17	N/A
Modality	0.00	0.00	0.00***
Residual	0.08	0.28	N/A

Note. $* p < 0.05$; $** p < 0.01$; $*** p < 0.001$.

As expected, Modality had a significant effect on children's RT, whereby children were quicker to respond using the numberpad (expected RT = 1060ms) compared to the floor mat (expected RT = 1190ms), t = -20.70, $p<0.001$. There was a significant effect of congruency, whereby children took longer to respond to incongruent stimuli (expected RT = 1250ms) relative to the congruent condition (expected RT = 1190ms), t = 16.54, $p < 0.001$. There was an effect of stimulus type, whereby children took significantly longer to respond to Arrow stimuli relative to Alien stimuli, t = 4.54, $p < 0.001$. There were no other significant contributors to the models variance.

DISCUSSION

In the present experiment, I investigated the effect of embodied cognition on children's inhibition. To do so, children took part in a modified flanker task that included an embodied condition (Aliens, floor mat) and a less embodied condition (Arrows,

numberpad). The purpose, to determine whether children's inhibition task performance was mediated by the addition of contextually relevant body actions – a core feature of embodied cognition theory. From previous investigations of children's floor mat interaction, I noted that the most often adopted movement on this device was to step between the directional keys. While this movement is arguable more physical in the sense that it engages the whole body (compared to pressing fingers on a keyboard) the quality of this movement was disconnected from the context of the task. Ideally, children would have hopped like frog to demonstrate they had 'embodied' the actions of the virtual character. So, in this experiment, I chose to create a context that matched this action – to 'squash' the target stimuli by stepping onto the floor mat's directional keys. First, I investigated the presence of the flanker effect to validate the task. Specifically, I expected that children's response accuracy would decrease and RT increase would when required to respond to incongruent stimuli. Secondly, I hoped to show that augmenting an embodied condition to the flanker task would provide further evidence that cognitive processes are indeed sensorimotor in nature. This embodied interpretation of EF would be supported by an improvement in task performance. The results of my analysis are discussed below.

Presence of the flanker effect

Analysis of the flanker effect revealed that congruency had a significant effect on performance, whereby children were more likely to respond incorrectly to incongruent flanker stimuli, relative to the congruent target stimuli. Note that neutral trials were removed from the analysis, as they were not of theoretical significance to the experiment and their omission allowed for model convergence. This result indicates the presence of the flanker effect, where participant judgement of the target stimulus' direction was impoverished by the presence of flanking, distractor stimuli. The effect occurred in both response modalities, showing that, inhibition can be demonstrated both in terms of participants visual processing of a stimulus, and by their physical representation of the task. Thus, the findings support the idea that motor control should be considered as an added component of EF (Rajendran & Mitchell, 2007). Much of the literature studying the EF profile of developmental disorders have taken a dualist approach (e.g. the Theory of Mind hypothesis of Autism; Baron-Cohen, 1985), treating cognition as a process involving the mind, and not a combination of both mind and body. My findings suggest

that to understand these developmental profiles consideration must also be given to the physical capabilities of the individual to fully appreciate their EF capabilities.

The effect of stimulus presentation

Additionally, the results revealed that children were less prone to error when responding to Alien stimuli, relative to arrow stimuli. This effect could be due to several reasons. Firstly, children were provided a meaningful context in the Alien condition; that planet earth had been invaded and it was up to them to be Earth's saviour by squashing the incoming Aliens. Providing a game like context to cognitive tasks has shown to improve children's level of engagement with the task (Arnab & Clarke, 2016). Therefore, children's performance on cognitive assessments is mediated by their level of engagement. The establish and growing popularity of video games is an indication that children are motivated and engage meaningfully with content that relates to their playful, imaginative nature. Research of gamification will help to clarify the conditions under which games harvest children's interests, to apply them to domains where they could be useful, such as cognitive intervention, training, and learning. Certainly, it appears that the mode of presentation, and the addition of a story helped to keep children focussed on a task that requires repeated application of a rule.

Another possible explanation for children's preference of the Alien stimuli is that children found determining the directionality of the Arrows harder because of their composition. Martiny-Huenger, Gollwitzer, and Oettingen (2014) recently found that participant ability to inhibit distractor stimuli is mediated by participant's mental representation of those distractor stimuli. Thus, it is conceivable that children found it easier to process the Alien stimuli as their composition was familiar (i.e. like a character from a TV show or computer game) relative to the angle bracket shape used for the Arrow stimuli. More extensive pilot testing with various flanker stimuli would aid in the selection of appropriate stimuli.

Effect of embodiment

The hypothesis that children would execute more correct and quicker responses in the embodied condition was not supported from the trends in the data. The number of errors children produced between embodied and less embodied version of the task was

similar, suggesting that the combination of manipulating the response format and the task presentation did not significantly alter children's comprehension of the task. What the results do demonstrate however, is that children's inhibition is not negatively affected by these manipulations. That is, children's ability to inhibit impulsive responses is as proficient while using a device that requires more physical activity, in a context that supports the type of action they execute. So, although the findings do not support embodiment as a catalyst for improving children's inhibitory processes, they support the interpretation that information processes and managing the incoming information presented by the flanker task, can be completed equally well with the body. This finding is positive in the sense that there is no loss of performance when children are required to move their bodies, a finding that could be used to develop health oriented EF interventions. There is already a growing literature examining the effect of exergames on children's EF (e.g. Staiano et al., 2012). There may be concerns that the additional physical component to EF tasks detracts from the executive elements. However, I have shown here that when asked to perform full body movements, children's inhibitory processes are as effective when sat down, pressing buttons on a numberpad.

Baseline EF and flanker task performance

Regarding the contribution of EF to task performance, children's scores on the Playing Cards subtest of the BADS-C explained a significant portion of the variance in children's response accuracy. From a closer inspection, this relationship indicated that children who were better at switching between the Playing Cards sorting dimensions ('Yes' to Red and 'No' to Black, followed by 'Yes' if the colour is the same as the one before it, 'No' if the colour is different to the one before it) were also better able to determine the direction of the target stimulus in the Flanker task. At a conceptual level, each task requires the participant to avoid interference from competing information. In the Playing Cards Task this information is verbal, as children should update their sorting strategy based on the new rule that is communicated to them verbally, as well as being visually present on a piece of card. Adept performance is marked by children's ability to remove the interfering information from the previous sorting rule. While generating a response in the Flanker task children must avoid the visual interference of the flanking stimuli in the Incongruent condition. Thus, in both tasks there is an element of interference that result in conflicting information at the point of response execution. This finding implicates the Flanker task as a measure of updating (also known as set shifting,

and cognitive flexibility), especially for incongruent trials, where children are forced to update their response strategy by rejecting the visual interference of the flanking stimuli. With respect to models of EF, the finding substantiates the claim that both these processes are inter-related. Further investigations of this link should include a range of updating tasks (e.g. Dimension Change Card Sort task; Zelazo, 2006) and the flanker task, to determine if inhibition and updating can be considered as a single cognitive construct.

Speed/accuracy trade off

A confound in the experiment was that children would take longer to respond to the target stimulus while using the floor mat relative to the numberpad. The well documented speed/accuracy trade-off effect is manifested by children's reduction in response accuracy when the time margin for response is reduced (Kail, 1991). Interestingly, I did not find such an effect in the analysis. The RT data confirmed that children took longer the generate a response using the floor mat but were as accurate at making responses when required to move their feet to the floor mats response buttons, to using their thumbs with the numberpad. This suggests that children were either highly proficient at providing correct responses regardless of time, or that the processes that govern decision making with the feet and body are as attuned to those responsible for finger pressing. Taking this line of enquiry further would suggest that children aged 7 years present equally effective fine and gross motor control. Recent investigations have shown that fine motor control at age four is a significant predictor of cognitive development and academic performance, more so that early gross motor control (Piek, Dawson, Smith, & Gasson, 2008). However, the following findings suggest later into primary education, both children's fine and gross motor movements are indicative of their cognitive functioning. Clearly, further work investigating the implications of children's fine and gross motor control and their relationship to cognition across the primary education years is needed to determine the point at which this plateau occurs.

CONCLUSION

In summary, children performed equally well on the task regardless of response modality or embodiment. Despite efforts to create a more and less embodied version of the task, the manipulations to both response generation modality and context (i.e. the games story) did not significantly alter task performance. On reflection, this outcome is

a positive one in that it demonstrates no loss of comprehension or ability. Children's inhibitory processes did not suffer when engaging their whole body as part of the tasks storyline. Interestingly, children provided more correct responses to Alien stimuli over Arrows. This finding provides support that gamification of a task improves children's motivation, and cognitive processing. Moreover, the relationship between children's performance on the Playing Cards assessment and their accuracy on the Flanker task questions the independence of the EF skills updating and inhibition. At a conceptual level, the conflicting information presented to children in the Incongruent trials, and the change of sorting rule in the playing card test suggests that inhibition and updating work in tandem to avoid interfering information. Lastly, the indication that children were as accurate while engaging both fine and gross motor control suggests that the benefit of fine motor control early in development may asymptote at around age 7 years. Further investigation of the relationship between motor control and cognition in the school years may be vital, as there may be a critical point at which motor abilities do not serve to improve cognition.

GENERAL DISCUSSION

This thesis examined children's multimodal interaction, and the effect of embodied cognition on EF. To do so, children completed two new computerised planning and inhibition tasks using a keyboard or numberpad, and a floor mat. Each task took inspiration from classic neuropsychological tests in the domain (i.e. Towers of London and the Flanker Task) and videogame design. Video games were used as a template for each tasks presentation given the popularity of this form of entertainment (Spence & Feng, 2010), and the literature demonstrating that repeated exposure to this medium can improve aspects of EF (Basak et al., 2008). However, rather than focus on the effects of repeated practice, or the benefits of specific game types, here I focussed on a new dimension to gaming: multimodal interaction. Multimodal interaction was of interest because this form of computing marks a shift away from traditional point-and-click modalities, to those that can be considered more attuned to human perceptual and sensory processes, for example, by facilitating whole body interaction (Oviatt, 2003). As these technologies continue to grow in utility and popularity, it is important to establish whether the type of interaction afforded by these devices is having a significant, positive impact on cognitive process. Indeed, recent findings indicate that completing a task with a multimodal interface rather than a traditional interface has advantageous effects on performance. Studies have shown these devices can improve short-term memory (Chao et al., 2013) and children's ability to estimate number magnitudes (Fischer et al., 2011). To consider the differences between interaction with traditional and multimodal interfaces I applied the theory of embodied cognition (e.g. Wilson, 2002). Previous studies of children's embodiment have shown that the addition of 'hands on' and physical interaction can aid their understanding of a task (Manches & O'Malley, 2010; Martin & Schwartz, 2005; O'Neill & Miller, 2013), although most of this literature examined non-digital materials in an educational context. Taking a slightly different approach, inspired by Chao et al. (2013), I asked children to complete EF tasks using two different interfaces that differed in their level of 'embodiment'. I predicted that children would perform better on tasks of EF using a floor mat because this device afforded a full-body experience and an embodied response format. Responses were embodied in the sense that children could 'offload' cognitive resources to the environment, and execute contextually relevant actions. For example, children could stamp on button of the mat, an action that was supported in the context of the flanker task. In the following, I discuss the effect of

embodiment, whether it was observed, and other possible interpretations of the findings. I also draw on my findings to further discuss the conceptual similarities between the theories of embodied cognition and EF, with a focus on children's motor coordination. Throughout the discussion, I make recommendations for future work, in terms of task development, and future studies in the field of children and technology. The limitations of the approach adopted are also explained. First, I draw attention to the effect of using a floor mat for response execution.

Children were better at the task while using the floor mat

For each experiment the focus was to determine if embodiment enabled children performed better on the task on either a floor mat or a keyboard/numberpad. Repeated measures were used to rigorously investigate this effect. For the most part, these performance comparisons yielded non-significant results. Generally, children were as effective either planning their route, or inhibiting a prepotent response while using the floor mat or the keyboard/numberpad. Initially, experiment 1 showed that children were better at planning using the keyboard, spending more time planning their first move and completing more trials optimally on the first attempt. My observations indicated that the floor mat setup posed more of a challenge to the keyboard, because children were forced to switch visual attention between the floor and the computer screen between each move. After modifications were made to account for this (in experiment 2), the pattern of planning competence shifted: children took more time to select their first move using the floor mat[7].. This effect demonstrates that when the demands of visually processing a task and physically executing a movement are reduced, children are more careful and deliberated in their approach. Ultimately though, this increase in initial thinking time did not result in a reduction in the number of moves executed – a key indicator of children's planning competence. Similarly, there was no statistically significant benefit to using the floor mat in experiment 3. Generating responses by squashing Aliens using their feet, or pressing buttons with their thumbs to match the direction of the middle Arrow did not significantly alter children's inhibitory processes. Further, the rigorous and conservative approach of mixed modelling ensured the results can be treated with confidence. These

---

[7] No such layout considerations were made for experiment 3, as responses were generated on fewer response keys that directly matched qualitative features of the stimuli (i.e. pointing either left or right).

findings raise several questions at a theoretical and practical level about the relationship between embodied cognition, executive function, and multimodal interfaces.

Embodied cognition and executive function

From the theoretical perspective, the purpose of contrasting performance between keyboard/numberpad and the floor mat was to demonstrate that *when cognition is embodied, task performance is enhanced.* Skills in the domain of EF were deliberately chosen as they are proposed to underlie the process of action execution (Denckla, 1996; Rajendran & Mitchell, 2007). Koziol and colleagues (2012) have gone as far to propose a model of cognition encompassing the logic of embodied cognition and EF, as part of a system that is responsible for conceptual grounding, through selective sensory and perceptual experience. Moreover, some have proposed that developmental disorders characterised by impairments in EF – such as Autism Spectrum Disorders (ASD; Robinson et al., 2009) – have motor control problems that underlie their cognitive profile (Damasio & Maurer 1978; Mostofsky, Burgess & Larson, 2007). So, research in the domain of EF indicates that this set of processes can be modulated by sensorimotor experiences. Although this link was not supported in my experimental findings there are several potential reasons to explain why the type of motor action, and indeed embodiment, did not cause an improvement in children EF. As stated, Piaget and Cook (1952) proposed that from birth to 24months infants steadily build up a repertoire of action schemas, the so called sensorimotor period. These sensorimotoric contingencies are conceptualised as the building blocks for symbolic representation, providing infants with their first cognitive referents, e.g. crying will get mother's attention. These experiences are highly contextual, taking place in certain settings, with certain individuals, under specific conditions. Understanding is generated from what we know from a young age, and this knowledge base started as a library of physical interactions. An important part of the embodied cognition argument is that by giving participants the opportunity to draw on these previous physical experiences the processing demands of the task is reduced (Glenberg & Kashak, 2002). So, determining the effects of embodied cognition with children requires a careful consideration of the type of physical experiences they have had in their environment hitherto. In Scotland, children in primary education are taught a range of computing skills with a traditional mouse and keyboard interface (Education Scotland, n.d.). Thus, when asked to complete each task, children had more sensorimotor experience with a keyboard to draw upon. Children's ability to complete the task more

effectively in experiment 1 demonstrated preferential processing of task information using this device. While using the keyboard, children took more time to plan their route and fewer moves to complete the block of trials. In contrast, the floor mat offered children the chance to apply a previously learned motor action (e.g. step, hop or jump) to a new context. The novelty of this interaction arguably increased the executive demands of task completion using the floor mat, and as already stated, may have interfered with their attention to the task Freier et al., 2015). However, it is important that I comment on the floor mat, and the interface design process. In the experiments presented in this thesis, the floor mat was chosen given its appropriate age range, ease of use with a laptop computer, and ability to facilitate whole body interaction. It is not a device that is currently used in school, although it has been used as part of the curriculum for physical activity (e.g. Unnithan, Houser, & Ferhall, 2005). What the results do indicate is that future projects studying children's embodied cognition, and multimodal interaction should carefully consider the child's prior physical experiences.

Another question that arises from the empirical work conducted in this thesis is the extent that completing each of the tasks could be considered embodied. Presently, there is no single definition of what embodied cognition entails (Wilson, 2002). However, some have highlighted that embodiment needs to be considered as a multisensory phenomenon, whereby the decision making is a culmination of both physical and sensory inputs. Studies of the 'body schema' indicate that the way an individual's processes their immediate, reachable surroundings – what is termed peripersonal space – can significantly impact the actions their cognition and behaviour. For instance, Ladavas (2002) discusses how right hemisphere damaged patients cannot detect stimulation to their contralateral hand when both hands are touched simultaneously. That is, despite visual recognition of physical stimulation in the peripersonal space, processing of the tactile information is subject to competition between the two hemispheres. For right hemisphere patients, this means that tactile stimulation to the right hand is given preference during bilateral double stimulations. Furthermore, visual stimulation to the right visual field during bilateral double stimulation removes this effect, demonstrating that peripersonal space is indeed coded with reference to bimodal, visual tactile information (di Pellegrino, Làdavas, & Farné, 1997). What these findings mean in terms of the following experiment is that children's tactile and visual stimulation during the experiment contributed to the manner that they understood the task. Experiment 3 required children to process visual information in the left and right visual field and to response accordingly with the corresponding foot. However, given that the tactile

feedback to both feet was constant throughout the experiment - from the padded floor mat - their ability to respond to stimuli appearing on the left side of the screen may have been compromised. That is, stimulation to both feet led to competition between each hemisphere, causing the dominant hemisphere to decide where cognitive resources be allocated. Moreover, while completing the flanker task children had to maintain visual focus on the screen in front of them, a source of direct sensory stimulation, but move their feet to two different locations in their peripersonal space (the left and right response buttons). Thus, their accuracy could have been mediated by their existing body schema, as their ability to pool together multiple sources of visual, tactile and proprioceptive information was tested in the act of standing up, facing forward, and stepping to the left or right as quickly as possible. So, the literature of body schema and peripersonal space shows that embodiment is a phenomenon that is more complex than consideration of the physicality or context of the movement. The neural processes that govern multisensory processing could have also played a significant role in children's conceptualisation and completion of the task.

Although multimodal interfaces that support whole body interaction are becoming more common place household items (e.g. Nintendo Wii), the extent that children are using the learning from these devices remains relatively unknown. In this sense, the findings reported here indicate that children think just as effectively with this technology. Another possible reason for the parity achieved between each device relates to children's ability to abstract away from the physical world.

Children's digital abstraction and presence

Of special interest in the thesis was the nature of response generation. Specifically, I focussed on whether the information processing preceding a response is mediated by embodiment. Embodiment was studied by manipulating the contextual relevance of the response action. Contextual relevance was theorised to be stronger on the floor mat as children were afforded the opportunity to re-enact the movements of a virtual character (i.e. hop like a frog), and stamp on Aliens as the lead protagonist in a fictional story. Previous studies of enactment have shown that adults working memory benefits when given the opportunity to act out contextualised actions relative to passive observation (Yang et al., 2014). The key difference in my experiments was that I examined children's

162

enactment of a virtual character, and if this additional dimension to response generation affect online cognition (i.e. during thinking, rather than retrospectively). So, inspection of children's movements therefore would indicate whether the child abstracted away from reality and imagined themselves as a part of the game. The video footage from experiment 2 demonstrated that although some children hopped like frogs during the task, most of the movements executed were decontextualized: stepping rather than hopping. One possible explanation for this pattern is that at this stage in development, children's ability to abstractly relate elements of a task (for this research, the response modality and the context of the 'story') is still developing. The effect of embodying the action of an avatar has previously shown beneficial effect on adult cognition. Chao et al. (2013) studied adults short term memory of verbal phrases (e.g. 'throw the ball') benefitted if they acted each phrase in front of a Kinect sensor that mapped their movements in real time to a virtual avatar. A separate group completed the actions with a mouse and keyboard recalled fewer phrases. The findings indicate that in adult's retention of information benefits when they take the 'mind's eye' of a virtual character. Although, the between-subject research method adopted in this research suggests that the differences between the groups could be specific to the samples composition, rather than modality. Other studies indicate that the children's cognition is mediated by the level of avatar customisability (Bailey, Wise, & Bolls, 2009). Thirty children aged 10 were either assigned, asked to choose from a set list, or fully customise an avatar prior to completing a videogame. Bailey et al. (2009) found the degree of personal customisation to be a significant factor in the extent that children felt a part of the game. Case in point, in experiments 1 and 2 children were assigned the role of a virtual frog to complete the game. Consequently, children may not have felt the level of 'presence' necessary to elicit an embodied action. Presence is defined as "the subjective experience of being in one place or environment, even when one is physically situated elsewhere" (Witmer & Singer, 1998). In the present experiment, presence would mediate the extent that children felt a part of the virtual environment – being Slippy for example – and thus the likelihood of adopting the actions of that character. The samples preference for stepping rather than hopping supports this idea. Giving children a virtual character created a level of dissociation from the tasks context. At present, there is a lack of information to determine whether these factors caused children to perform similarly on the floor mat and keyboard. It is possible that the virtual frog did not capture draw children into the virtual environment. Alternatively, the ability to abstract in a virtual world is immature at the age of 7. Future work should continue to study the parameters that affect learning with an

avatar and immersive environments. Studies of avatar customisation may prove particularly fruitful in this area, as children have the chance to create digital versions of themselves, thereby affording the researchers the opportunities to examine the implications of presence on cognition. Taking a different perspective, the similarities in performance between each modality suggests that by age 7 years' children are just as competent coordinating their feet as they are with their fingers.

Children aged 7 years are competent 'body thinkers'

With respect to the motor system, keyboard interaction could be considered as primarily visual, since the motor requirements of the response generation were limited. However, while using the floor mat, children are forced to conceptualise the task in terms of both the visual and motor elements of response generation, thereby drawing on the different type of cognitive model in the decision-making process. Interestingly, both experiments 2 and 3 demonstrate that children aged 7 do not suffer from a source of perceptual advantage or interference between each of the response modalities. That is, that children were as component responding to stimuli when the response modality and perceptual element of the task could be considered embodied. This finding is somewhat contradictory to recent evidence implicating the role of gross motor control as a precursor of working memory and processing speed (Piek et al., 2008). If gross motor control predicts the development of other executive components, then it is reasonable to infer that either a) children would perform better on each task using the floor mat, or b) that children's gross motor coordination – as measured by the DCCDQ'07 – would account for a significant portion of the variance in the flanker task. The results did not indicate a preference for fine or gross motor control. Thus, is it conceivable that planning and inhibition are abilities that are not mediated by these different forms of motor coordination. This finding contradicts previous work in the area as Hartman and colleagues (2010) found that combining children's fine and gross motor abilities predicted their inhibition performance. Moreover, Rahmi-Golkanden et al., (2016) showed a similar relationship, as their sample of children with DCD were less able to without impulsive decision making. I found no associated between children's behavioural fine and gross motor skills from the task, or from parent reports of motor control functioning with inhibition. A possible explanation for the lack of effect witnessed is that only typically developing children took part in my experiments. Given the association between disordered development and atypical motor coordination, it is possible that, even

if some children in the sample possessed below-average fine or gross motor skills, the variance in performance would be minimal. In other words, the relationship between motor coordination and EF is less evident for typically developing children as the processes that underlie controlled, deliberate movement and decision making develop in parallel without disruption. As Diamond (2000) pointed out, the pre-frontal and motor cortex show a similar protracted period of neural development, in terms of the influx of neural connections. Therefore, future work that seeks to determine the impact of motor control on EF using multimodal technologies should consider including a group of children with a developmental disorder.

Multimodality encourages a careful problem solving approach

Another feature of children's performance that supports their body based thinking is the data of children's planning time and optimal first time completions from experiment 2. Children's initial thinking times were significantly longer while using the floor mat in this experiment, showing that when the body becomes a part of the decision-making process, children are more careful and deliberated in their approach. This suggests that while using the floor mat children invested more time and effort to solving the onscreen puzzle as they were an active protagonist in the context of the task. That is, the cost of making an error or selecting the incorrect route in the planning task was perceived to be higher when responses were generated by physical movement, as opposed to a few button presses. However, this increase in planning time did not results in better planning performance, wither differences between the two interfaces not reaching significance. Nonetheless, the finding suggests that the data that studies of children's planning, and other EF abilities should consider response modality. Several modern iterations of EF tasks (e.g. the Cambridge Neuropsychological Test Battery, or CANTAB) use touchscreen devices to measure performance, such as a tablet. And, as children's behaviour is generated in a 3-dimensional environment, not on a 2-dimensional surface, I argue that multimodal interfaces provide a better indication of a child's EF functioning in the 'real world' (Turk, 2014). Put differently, the floor mat gave me the opportunity to examine the factors that influenced physical decision making, beyond other EF table based or computerised tests. This point is especially pertinent given the indication that EF performance in a laboratory setting does not match to real world settings (Anderson, 2002). Thus, multimodal interfaces should be considered as part of future EF assessment, given that children's thinking is not impaired with the addition of physical movement.

Practice effects and the optimal number of moves

Experiment's 1 and 2 studied the effect of the number of moves to completion on children's planning performance. Previous literature in the area has found that this number serves as a proxy for task difficulty, as participant are forced to search through a larger problem space when the number of moves required is greater (Newell, 1980; Unterrainer et al., 2013). I applied this logic to the trials in Slippy's Adventure, hoping to demonstrate that the number of moves in a Tower configuration was analogous to the number of moves children had to plan. Initially, this relationship was not upheld, as children were better at 4-move trials in experiment 1. I suggested that these differences may have been due to practice effects, as the order of presentation was fixed: ten 3-move trials followed by ten 4-move trials. Adjusting the experiment to include 5- and 6-move trials with fewer trials per factor yielded the expected effect of optimal number of moves. In experiment 2, the effect was more linear, with children spending longer and taking more additional moves to complete more complex trials. Hence, future studies of planning should take my experience into consideration when developing materials. Seemingly, asking children to complete ten trials of the same level consecutively can significantly increase the likelihood of practice effects occurring. A better approach to take is to reduce the number of trials for each level, and to increase the number of levels in that factor.

Videogame and task performance

In experiment 2 I examined whether children's videogame experience affected their task performance. Parents of each participant completed a questionnaire pertaining to their child's weekly videogame habits. Of interest was the amount of screen time children had, and their weekly allowance of videogame play. The results indicated that children who played between 1-5 hours of video games per week were faster at completing trials successfully, to children who did not play video games. From a cognitive perspective, the finding suggests that the skills required to plan are trained by video games, and therefore, that videogame play enhanced children's ability to break down a problem into its constituent parts and execute the optimal route to completion. This finding is unsurprising given the demands of video games for children. A core feature of video games is that they are challenging but also fun and rewarding (Spence & Feng, 2010). Completing levels in videogames often requires a certain degree of planning,

for example, to determine if your avatar has enough resources or the right skills level to upgrade or attain a mission critical item. As progress is made through a game, the level of challenge increases, thereby requiring more planning. Hence, videogame play requires EF as players must mentally represent a problem and judge on the fly the likelihood of successful progression based on the avatars ability level. In my experiment, the finding suggests that weekly videogame play enhanced children's ability to find a solution to a maze-like task. This is somewhat unsurprising given that many video games designed for children focus on spatial problem solving. Minecraft an almost virtual equivalent to Lego, encourages both problem-solving and conceptual development skills (Schifter & Cipollone, 2015). Hence, it is possible that those skills children trained at home as part of the leisure gaming routine transferred to their planning performance in Slippy's Adventure. In the construction mode in Minecraft players are encouraged to carefully plan a set of objectives to build, and create 3-D habitable spaces. So, in a similar manner to Slippy's adventure, successful completion of a task is determined by the child's ability to identify the end-goal, break down the goal into its constituent operators, and execute those steps in a logical order. Identification and selection of the optimal planning route is thus akin to laying the correct number of virtual bricks for a building's foundation. So, future interest should lie in an analysis of both the games constituent cognitive components and cross reference this information with the ascribed genre. Doing so will allow developers to make more informed decisions related to educational games, and EF interventions (e.g. identify game types that tap this ability). The current videogame market is saturated with games that are built around the principles of challenge and fun (Gee, 2014). There is no reason why the core principles of EF could be incorporated into this media in a similar manner.

Additionally, children were better at determining the direction of the target stimulus in experiment 3 when the stimulus qualitatively resembled a videogame. Incongruent Alien stimuli posed less of a challenge to children to the Arrow (angled brackets) stimuli. The finding suggest that children's inhibitory processes benefitted by the mode of presentation, and perhaps that gamifying the task was more *in tune* with their cognitive processes. The Alien stimuli were chosen for the experiment to leverage children's interest in the subject matter. Aliens are a popular topic in both children's TV and videogame media (Livingstone et al., 2014), and children's movies with Aliens as the focal topic, such as Minions (2015), grossing over 1 billion US dollars worldwide. I have already stressed the importance of prior experience to children's cognitive functioning, and the results of this experiment emphasise this point once more. The Alien stimuli had

colour, facial characteristics, and meaning in the context of the experiment (i.e. invaders of planet Earth). Conversely, the Arrow stimuli were simple black angled brackets. I argue that stimuli of this composition are less familiar to children, who are brought up in an environment filled with colour, shapes, letters and numbers. Due to their unfamiliarity, children were poorer at determining if angled brackets faced left or right, as response generation required a degree of motivation and meaningful understanding. Squashing incoming Aliens on the other hand was an activity that carried meaning and familiarity. In summary, I contend that children's enhanced performance on the Alien flanker task reflected the current trend in children's media, and the game-like presentation of the task.

Children's perceptual reasoning skills predicted planning performance

An additional finding from experiment 2 was that children planning performance related to their perceptual reasoning skills. Children who scored highly on the Matrix Reasoning subtest of the WAIS-II took less time to plan their route when a trial was completed optimally. Moreover, high achievers on the Block Design subtest executed fewer invalid moves. This finding feeds into a growing literature demonstrating that intelligence and EF relate to one another. Friedman et al. (2006) found that working memory, but not inhibition predicted children's EF, suggesting that certain only specific skills part of the EF umbrella contribute to the concept of intelligence. Slippy's Adventure was designed with the intention to test children planning skills. By breaking down planning into its constituent parts provides a clearer indication of why this skill drew on children's perceptual reasoning. Good planning involves the identification of a goal, its componential operators, and mental simulation of an identified path (Newell & Simon, 1972). To complete a trial successfully in Slippy's Adventure, children had to select an optimal route by identifying the goal (the golden lily pad), cross reference the operators with the number of moves presented in the top left hand corner of the screen, and execute the route that matched this number. This has similar elements to both the Matrix Reasoning and Block Design subtests of the WAIS-II as the identification of goal related elements from a given set are necessary prior to selecting a course of action. For example, in Block Design, success is achieved by children's ability to cross reference the target pattern with the potential picture composition afforded by the blocks. Hence, the research provides further support for the conceptual link between EF and intelligence. Perceptual reasoning skills are important for problem deconstruction and planning.

Future implications

Children are brought up in an environment saturated with digital technologies. These technologies are becoming more ubiquitous as tools for learning, human interaction, business and play. Digital technologies are becoming integral to human's functional purposes (Clark, 2001) shaping the way information is grounded by children (Prensky, 2001). By providing a human touch to human-computer interaction, multimodal interfaces erode the communicative styles between man and machine. As we enter an age where devices like these become more able to support human-like forms of communication and interaction the question about whether cognition is embodied becomes more pertinent. It is possible for example, that future computers will not have a keyboard like the one I am typing on now. Instead, word processing may be achieved by swiping a virtual space in front of me, what could be termed 'virtual swipe-typing'. This in turn will change the way that I conceptualise the act of typing, to one that is not bound to a certain space and spatial layout of keys, but one whereby composition consists of freely swiping the hands, executing delicate movements akin to an orchestral conductor. This may seem a farfetched for now, but consider recent innovations in user interface design in the last two decades with the advent of touchscreen smartphones, gestural interfaces, eye-tracking computer interfaces, and more recently, virtual and augmented reality headsets. Each of these technologies attempts to shift away from the traditional computing format to one that suits the human perceptual and sensory systems. As children are going to experience this technological evolution, investigating the implications of this change in human-computer interaction is important. The studies outlined in this thesis aimed to address this issue.

CONCLUSION

This was one of the first investigations of embodied cognition in the domain of EF, and children's cognitive development. Together, the findings show that using the platform of video games to assess children's cognition is a valid method and that multimodal interfaces and traditional interfaces provide equally good support for children's thinking. That is, cognitive tasks inspired by videogames provide a window to children's information processing, and that this processing is are effective when sedentary or physical in children aged 7 years old. As the research effort continues in the domain of

169

EF, in terms of intervention and theoretical understanding, this thesis highlights an important aspect of future computer interaction in this area. That is, even when the times comes where keyboard and mice are obsolete technologies, that the multimodal interfaces of the future will support children's thinking and learning just as effectively. Moreover, the physical activity afforded by these devices suggests that other health related factors could be factored in to intervention programmes.

Consider that now, and even more so in the future, content for both play and education with be presented to children in a digital format. The videogame industry is awash with games aimed at training skills and teaching principles important to cognitive functioning across the lifespan. I have demonstrated that materials for this purpose can be presented in multimodal format, without resulting in significant decreased in understanding and performance. A concern among parents and academics is that video games are merely another form of play, and do not offer the same formal instruction offered in the classroom. However, videogame based learning is an activity that takes place in both the home and the classroom (Takuechi & Vaala, 2014). As videogame consoles are present in many homes across the UK it is up to psychologists and computer scientists to share their expertise to create media that is both fun and informative for children. Research of EF demonstrates that these skills are vital to children's functioning academic attainment (Blair & Razza, 2009) and social functioning (Pellicano, Maybery, Durkin, & Maley, 2006). The interdisciplinary studies in this thesis demonstrate that bringing together expertise from computer science and psychology is a fruitful venture, for the development of EF assessment materials. Exchanging knowledge made it possible to develop a task that was phenomenologically relevant (i.e. tested embodied cognition) and fun for children. Research to date of serious or cognitive training games (e.g. Cogmed) continues to exemplify innovations in the field of tools for pedagogy. As EF is important for typical and atypical development, efforts should continue to study the parameters that affect performance on game like EF tasks. The findings from experiment 3 show that children were better at inhibiting the interference from flanking stimuli when the stimuli were game likes (Aliens), and therefore, could be more attuned with the processing style adopted by children aged 7 years. Future assessments of EF therefore could take a similar form: by moving away from the format offered by research of adult neuropsychology, to a more modern game like presentation. Otherwise, the ability of children to plan, inhibit a response, and think carefully about the action they are about to execute is underestimated.

References

American Association on Intellectual and Developmental Disabilties (AAIDD). (2007). Definition of Mental retardation 2007. Retrieved 13 July 2016, from http://www.aamr.org

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC.

Amieva, H., Phillips, L., & Della Sala, S. (2003). Behavioral dysexecutive symptoms in normal aging. *Brain and cognition, 53*(2), 129-132.

Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology, 8*(2), 71-82.

Anzai, Y., & Simon, H. A. (1979). The theory of learning by doing. *Psychological review, 86*(2), 124.

Arnab, S., & Clarke, S. (2016). Towards a trans-disciplinary methodology for a game-based intervention development process. *British Journal of Educational Technology*.

Avenanti, A., Candidi, M., & Urgesi, C. (2013). Vicarious motor activation during action perception: beyond correlational evidence. *Front Hum Neurosci 2013 May; 7, 185*(2,906).

Baddeley, A. (1986). *Working memory*. Oxford, England: Oxford University Press.

Baddeley, A. (2010). Working memory. *Current biology, 20*(4), R136-R140.

Baddeley, A., Chincotta, D., & Adlam, A. (2001). Working memory and the control of action: evidence from task switching. *Journal of experimental psychology: General, 130*(4), 641.

Bailey, R., Wise, K., & Bolls, P. (2009). How avatar customizability affects children's arousal and subjective presence during junk food–sponsored online video games. *CyberPsychology & Behavior, 12*(3), 277-283.

Banich, M. T. (2009). Executive function the search for an integrated account. *Current Directions in Psychological Science, 18*(2), 89-94.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: constructing a unifying theory of ADHD. *Psychological bulletin, 121*(1), 65.

Baron-Cohen, S., Leslie, A. M., & Frith, U. (1985). Does the autistic child have a "theory of mind"? *Cognition, 21*(1), 37-46.

Basak, C., Boot, W. R., Voss, M. W., & Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychology and aging, 23*(4), 765.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). lme4: Linear mixed-effects models using Eigen and S4. *R package version, 1*(7).

Bavelier, D., Green, C. S., Han, D. H., Renshaw, P. F., Merzenich, M. M., & Gentile, D. A. (2011). Brains on video games. *Nature Reviews Neuroscience, 12*(12), 763-768.

Benes, F. M. (2001). The development of prefrontal cortex: The maturation of neurotransmitter systems and their interactions. *Handbook of developmental cognitive neuroscience, 2*, 79-92.

Bennett, S., Maton, K., & Kervin, L. (2008). The 'digital natives' debate: A critical review of the evidence. *British Journal of Educational Technology, 39*(5), 775-786.

Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child development, 81*(6), 1641-1660.

Biederman, J., Monuteaux, M. C., Doyle, A. E., Seidman, L. J., Wilens, T. E., Ferrero, F., . . . Faraone, S. V. (2004). Impact of executive function deficits and attention-

deficit/hyperactivity disorder (ADHD) on academic outcomes in children. *Journal of consulting and clinical psychology, 72*(5), 757.

Bioulac, S., Arfi, L., & Bouvard, M. P. (2008). Attention deficit/hyperactivity disorder and video games: A comparative study of hyperactive and control children. *European Psychiatry, 23*(2), 134-141.

Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child development, 78*(2), 647-663.

Bloedel, J. R., & Bracha, V. (1996). Duality of cerebellar motor and cognitive functions. *International review of neurobiology, 41*, 613-634.

Boot, W. R., Kramer, A. F., Simons, D. J., Fabiani, M., & Gratton, G. (2008). The effects of video game playing on attention, memory, and executive control. *Acta psychologica, 129*(3), 387-398.

Brunamonti, E., Chiricozzi, F. R., Clausi, S., Olivito, G., Giusti, M. A., Molinari, M., . . . Leggio, M. (2014). Cerebellar damage impairs executive control and monitoring of movement generation. *PloS one, 9*(1), e85997.

Brydges, C. R., Reid, C. L., Fox, A. M., & Anderson, M. (2012). A unitary executive function predicts intelligence in children. *Intelligence, 40*(5), 458-469.

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental neuropsychology, 33*(3), 205-228.

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental neuropsychology, 19*(3), 273-293.

Burgess, P. W., Alderman, N., Evans, J., Emslie, H., & Wilson, B. A. (1998). The ecological validity of tests of executive function. *Journal of the international neuropsychological society, 4*(06), 547-558.

Cameron, C. E., Brock, L. L., Murrah, W. M., Bell, L. H., Worzalla, S. L., Grissmer, D., & Morrison, F. J. (2012). Fine motor skills and executive function both contribute to kindergarten achievement. *Child development, 83*(4), 1229-1244.

Carlson, S. M. (2005). Developmentally sensitive measures of executive function in preschool children. *Developmental neuropsychology, 28*(2), 595-616.

Carlson, S. M., Mandell, D. J., & Williams, L. (2004). Executive function and theory of mind: stability and prediction from ages 2 to 3. *Developmental Psychology, 40*(6), 1105.

Casey, B., Somerville, L. H., Gotlib, I. H., Ayduk, O., Franklin, N. T., Askren, M. K., . . . Teslovich, T. (2011). Behavioral and neural correlates of delay of gratification 40 years later. *Proceedings of the National Academy of Sciences, 108*(36), 14998-15003.

Castel, A. D., Pratt, J., & Drummond, E. (2005). The effects of action video game experience on the time course of inhibition of return and the efficiency of visual search. *Acta psychologica, 119*(2), 217-230.

Chao, K. J., Huang, H. W., Fang, W. C., & Chen, N. S. (2013). Embodied play to learn: Exploring Kinect-facilitated memory performance. *British Journal of Educational Technology, 44*(5), E151-E155.

Chaytor, N., Schmitter-Edgecombe, M., & Burr, R. (2006). Improving the ecological validity of executive functioning assessment. *Archives of Clinical Neuropsychology, 21*(3), 217-227.

Clark, A. (2001). Natural-born cyborgs? *Cognitive Technology: Instruments of Mind* (pp. 17-24): Springer Berlin Heidelberg.

Connolly, T. M., Boyle, E. A., MacArthur, E., Hainey, T., & Boyle, J. M. (2012). A systematic literature review of empirical evidence on computer games and serious games. *Computers & Education, 59*(2), 661-686.

Cook, R., Bird, G., Catmur, C., Press, C., & Heyes, C. (2014). Mirror neurons: from origin to function. *Behavioral and brain sciences, 37*(02), 177-192.

Crawley, M. (2013). The R Book. Ed. *Wiley, 5*, 744.

Cummings, A. H. (2007). *The evolution of game controllers and control schemes and their effect on their games.* Paper presented at the The 17th Annual University of Southampton Multimedia Systems Conference.

Dalsgaard, S. (2013). Attention-deficit/hyperactivity disorder (ADHD). *European child & adolescent psychiatry, 22*(1), 43-48.

Damasio, A. R., & Maurer, R. G. (1978). A neurological model for childhood autism. *Archives of neurology, 35*(12), 777-786.

Damasio, H., Grabowski, T., Frank, R., Galaburda, A. M., & Damasio, A. R. (1994). The return of Phineas Gage: clues about the brain from the skull of a famous patient. *Science, 264*(5162), 1102-1105.

De Luca, C. R., Wood, S. J., Anderson, V., Buchanan, J.-A., Proffitt, T. M., Mahony, K., & Pantelis, C. (2003). Normative data from the CANTAB. I: development of executive function over the lifespan. *Journal of Clinical and experimental Neuropsychology, 25*(2), 242-254.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of experimental psychology: General, 122*(3), 371.

Delis, D. C., Kaplan, E., & Kramer, J. H. (2001). *Delis-Kaplan executive function system (D-KEFS)*: Psychological Corporation.

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review, 12*(1), 45-75.

Dempster, F. N. (1993). Resistance to interference: Developmental changes in a basic processing mechanism *Emerging themes in cognitive development* (pp. 3-27): Springer.

Denckla, M. B. (1996). A theory and model of executive function: A neuropsychological perspective.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child development, 71*(1), 44-56.

Diamond, A. (2013). Executive functions. *Annual review of psychology, 64*, 135.

Diamond, A., Barnett, W. S., Thomas, J., & Munro, S. (2007). Preschool program improves cognitive control. *Science (New York, NY), 318*(5855), 1387.

di Pellegrino, G., Làdavas, E., & Farné, A. (1997). Seeing where your hands are. *Nature, 388*(6644), 730-730.

Durkin, K., & Aisbett, K. (1999). Computer games and Australians today.

Durkin, K., & Blades, M. (2009). Young people and the media: Special Issue. *British Journal of Developmental Psychology, 27*(1), 1-12.

Education Scotland. (n.d.). *Technologies: experiences and outcomes*. http://www.educationscotland.gov.uk/: Retrieved from http://www.educationscotland.gov.uk/learningandteaching/curriculumareas/technologies/eandos/index.asp.

Emslie, H., Burden, V., Nimmo-Smith, I., Wilson, B. A., & Wilson, C. (2003). *Behavioural assessment of the dysexecutive syndrome for children*: Thames Valley Test Company.

Engel-Yeger, B., Josman, N., & Rosenblum, S. (2009). Behavioural Assessment of the Dysexecutive Syndrome for Children (BADS-C): An examination of construct

validity. *Neuropsychological Rehabilitation, 19*(5), 662-676. doi: 10.1080/09602010802622730

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & psychophysics, 16*(1), 143-149.

Eriksen, C. W., & Schultz, D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & psychophysics, 25*(4), 249-263.

Fischer, U., Moeller, K., Bientzle, M., Cress, U., & Nuerk, H.-C. (2011). Sensori-motor spatial training of number magnitude representation. *Psychonomic Bulletin & Review, 18*(1), 177-183.

Freier, L., Cooper, R. P., & Mareschal, D. (2015). The planning and execution of natural sequential actions in the preschool years. *Cognition, 144*, 58-66.

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., DeFries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological science, 17*(2), 172-179.

Gallese, V. (2014). Bodily selves in relation: embodied simulation as second-person perspective on intersubjectivity. *Phil. Trans. R. Soc. B, 369*(1644), 20130177.

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

Gee, J. P. (2014). *What video games have to teach us about learning and literacy*: Macmillan.

Geurts, H. M., Verté, S., Oosterlaan, J., Roeyers, H., & Sergeant, J. A. (2004). How specific are executive functioning deficits in attention deficit hyperactivity disorder and autism? *Journal of child Psychology and Psychiatry, 45*(4), 836-854.

Glenberg, A. M. (2010). Embodiment as a unifying perspective for psychology. *Wiley Interdisciplinary Reviews: Cognitive Science, 1*(4), 586-596.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review, 9*(3), 558-565.

Goldin-Meadow, S., & Beilock, S. L. (2010). Action's influence on thought: The case of gesture. *Perspectives on Psychological Science, 5*(6), 664-674.

Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining math: Gesturing lightens the load. *Psychological science, 12*(6), 516-522.

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature, 423*(6939), 534-537.

Harlow, J. M. (1868). Recovery from the passage of an iron bar through the head. *Publications of the Massachusetts Medical Society, 2*(3), 327-246.

Hartman, E., Houwen, S., Scherder, E., & Visscher, C. (2010). On the relationship between motor performance and executive functioning in children with intellectual disabilities. *Journal of Intellectual Disability Research, 54*(5), 468-477.

Holmes, J., Gathercole, S. E., & Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental science, 12*(4), F9-F15.

Hunter, S. J., & Sparrow, E. P. (2012). *Executive function and dysfunction: Identification, assessment and treatment*: Cambridge University Press.

Interactive Software Federation of Europe. (2012). GameTrack: Q2 2012 results summary.

Internet Advertising Bureau UK. (2014). Gaming Revolution.

Jacques, S., & Zelazo, P. D. (2001). The Flexible Item Selection Task (FIST): A measure of executive function in preschoolers. *Developmental neuropsychology, 20*(3), 573-591.

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological bulletin, 109*(3), 490.

Kaller, C. P., Rahm, B., Spreer, J., Mader, I., & Unterrainer, J. M. (2008). Thinking around the corner: The development of planning abilities. *Brain and cognition, 67*(3), 360-370.

Kaller, C. P., Unterrainer, J. M., Rahm, B., & Halsband, U. (2004). The impact of problem structure on planning: Insights from the Tower of London task. *Cognitive Brain Research, 20*(3), 462-472.

Knight, R. T., & Stuss, D. T. (2002). Prefrontal cortex: The present and the future. *Principles of frontal lobe function*, 573-597.

Koziol, L. F., Budding, D. E., & Chidekel, D. (2012). From movement to thought: executive function, embodied cognition, and the cerebellum. *The Cerebellum, 11*(2), 505-525.

Kuhn, L. J., Willoughby, M. T., Wilbourn, M. P., Vernon-Feagans, L., & Blair, C. B. (2014). Early communicative gestures prospectively predict language development and executive function in early childhood. *Child development, 85*(5), 1898-1914.

Làdavas, E. (2002). Functional and dynamic properties of visual peripersonal space. *Trends in cognitive sciences, 6*(1), 17-22.

Lakoff, G., & Johnson, M. (1980). Metaphors We Live By: Chicago: University of Chicago Press.

Lakoff, G., & Núñes, R. (2000). *Where Mathematics Comes From: How the Embodied Mind Brings Mathematics into Being*. New York: Basic Books.

Lee, K., Bull, R., & Ho, R. M. (2013). Developmental changes in executive functioning. *Child development, 84*(6), 1933-1953.

Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment six precepts for research on embodied learning and mixed reality. *Educational Researcher, 42*(8), 445-452.

Livingstone, S., Marsh, J., Plowman, L., Ottovordemgentschenfelde, S., & Fletcher-Watson, B. (2014). Young children (0-8) and digital technology: a qualitative exploratory study-national report-UK.

Lo, S., & Andrews, S. (2015). To transform or not to transform: using generalized linear mixed models to analyse reaction time data. *Frontiers in psychology, 6*.

Lopez, B. R., Lincoln, A. J., Ozonoff, S., & Lai, Z. (2005). Examining the relationship between executive functions and restricted, repetitive symptoms of autistic disorder. *Journal of Autism and Developmental disorders, 35*(4), 445-460.

Luria, A., Karpov, B., & Yarbuss, A. (1966). Disturbances of active visual perception with lesions of the frontal lobes. *Cortex, 2*(2), 202-212.

Manches, A., O'Malley, C., & Benford, S. (2010). The role of physical representations in solving number problems: A comparison of young children's use of physical and virtual materials. *Computers & Education, 54*(3), 622-640.

Martin, T., & Schwartz, D. L. (2005). Physically distributed learning: Adapting and reinterpreting physical environments in the development of fraction concepts. *Cognitive science, 29*(4), 587-625.

Martinovic, D., Burgess, G. H., Pomerleau, C. M., & Marin, C. (2016). Computer games that exercise cognitive skills: What makes them engaging for children? *Computers in Human Behavior, 60*, 451-462.

Martiny-Huenger, T., Gollwitzer, P. M., & Oettingen, G. (2014). Distractor devaluation in a flanker task: Object-specific effects without distractor recognition memory. *Journal of Experimental Psychology: Human Perception and Performance, 40*(2), 613.

McCarron, L. T. (1997). *MAND: McCarron assessment of neuromuscular development, fine and gross motor abilities*: McCarron-Dial Systems, Incorporated.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive psychology, 41*(1), 49-100.

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., . . . Ross, S. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences, 108*(7), 2693-2698.

Montani, V., De Grazia, M. D. F., & Zorzi, M. (2014). A new adaptive videogame for training attention and executive functions: design principles and initial validation.

Mostofsky, S. H., Burgess, M. P., & Larson, J. C. G. (2007). Increased motor cortex white matter volume predicts motor impairment in autism. *Brain, 130*(8), 2117-2122.

Needham, A., Barrett, T., & Peterman, K. (2002). A pick-me-up for infants' exploratory skills: Early simulated experiences reaching for objects using 'sticky mittens' enhances young infants' object exploration skills. *Infant Behavior and Development, 25*(3), 279-295.

Nemeth, D., Turcsik, A. B., Farkas, G., & Janacsek, K. (2013). Social communication impairs working-memory performance. *Applied Neuropsychology: Adult, 20*(3), 211-214.

Newell, A., & Simon, H. A. (1972). *Human problem solving* (Vol. 14): Prentice-Hall Englewood Cliffs, NJ.

Nitschke, K., Ruh, N., Kappler, S., Stahl, C., & Kaller, C. P. (2012). Dissociable stages of problem solving (I): Temporal characteristics revealed by eye-movement analyses. *Brain and cognition, 80*(1), 160-169.

Norman, D., & Shallice, T. (1980). Attention to action: willed and automatic control of behavior: DTIC Document.

O'Neill, G., & Miller, P. H. (2013). A show of hands: Relations between young children's gesturing and executive function. *Developmental Psychology, 49*(8), 1517.

Ohbayashi, M., Ohki, K., & Miyashita, Y. (2003). Conversion of working memory to motor sequence in the monkey premotor cortex. *Science, 301*(5630), 233-236.

Olson, C. K. (2010). Children's motivations for video game play in the context of normal development. *Review of General Psychology, 14*(2), 180.

Oviatt, S. (2003). Multimodal interfaces. *The human-computer interaction handbook: Fundamentals, evolving technologies and emerging applications*, 286-304.

Ozonoff, S., & McEvoy, R. E. (1994). A longitudinal study of executive function and theory of mind development in autism. *Development and psychopathology, 6*(03), 415-431.

Ozonoff, S., Pennington, B. F., & Rogers, S. J. (1991). Executive function deficits in high-functioning autistic individuals: relationship to theory of mind. *Journal of child Psychology and Psychiatry, 32*(7), 1081-1105.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*: Basic Books, Inc.

Papesh, M. H. (2015). Just out of reach: On the reliability of the action-sentence compatibility effect. *Journal of experimental psychology: General, 144*(6), e116.

Pellicano, E., Maybery, M., Durkin, K., & Maley, A. (2006). Multiple cognitive capabilities/deficits in children with an autism spectrum disorder:" Weak" central coherence and its relationship to theory of mind and executive control. *Development and psychopathology, 18*(1), 77.

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of child Psychology and Psychiatry, 37*(1), 51-87.

Piaget, J., Cook, M., & Norton, W. (1952). *The origins of intelligence in children* (Vol. 8): International Universities Press New York.

Piek, J. P., Dawson, L., Smith, L. M., & Gasson, N. (2008). The role of early fine and gross motor development on later motor and cognitive ability. *Human movement science, 27*(5), 668-681.

Piek, J. P., Dyck, M. J., Nieman, A., Anderson, M., Hay, D., Smith, L. M., . . . Hallmayer, J. (2004). The relationship between motor coordination, executive functioning and attention in school aged children. *Archives of Clinical Neuropsychology, 19*(8), 1063-1076.

Ping, R. M., & Goldin-Meadow, S. (2008). Hands in the air: using ungrounded iconic gestures to teach children conservation of quantity. *Developmental Psychology, 44*(5), 1277.

Plato. (2008). Phaedrus. 2016, from http://www.academia.edu/610762/Neuropolitik_und_plastische_Gehirne_-_Eine_Fallstudie_des_adoleszenten_Gehirns

Pouw, W. T., Van Gog, T., & Paas, F. (2014). An embedded and embodied cognition review of instructional manipulatives. *Educational Psychology Review, 26*(1), 51-72.

Prensky, M. (2001). Digital natives, digital immigrants part 1. *On the horizon, 9*(5), 1-6.

Proffitt, D. R. (2013). An embodied approach to perception by what units are visual perceptions scaled? *Perspectives on Psychological Science, 8*(4), 474-483.

R Core Team. (2016). R: A Language and Environment for Statistical Computing. from https://www.R-project.org/

Rahimi-Golkhandan, S., Steenbergen, B., Piek, J., Caeyenberghs, K., & Wilson, P. (2016). Revealing hot executive function in children with motor coordination problems: What's the go? *Brain and cognition, 106*, 55-64.

Rajendran, G. (2013). Virtual environments and autism: a developmental psychopathological approach. *Journal of Computer Assisted Learning*.

Rajendran, G., & Mitchell, P. (2007). Cognitive theories of autism. *Developmental Review, 27*(2), 224-260.

Riccio, C. A., & Gomes, H. (2013). Interventions for executive function deficits in children and adolescents. *Applied Neuropsychology: Child, 2*(2), 133-140.

Riggs, N. R., Jahromi, L. B., Razza, R. P., Dillworth-Bart, J. E., & Mueller, U. (2006). Executive function and the promotion of social–emotional competence. *Journal of Applied Developmental Psychology, 27*(4), 300-309.

Rigoli, D., Piek, J. P., Kane, R., Whillier, A., Baxter, C., & Wilson, P. (2013). An 18-month follow-up investigation of motor coordination and working memory in primary school children. *Human movement science, 32*(5), 1116-1126.

Risko, E. F., & Dunn, T. L. (2015). Storing information in-the-world: Metacognition and cognitive offloading in a short-term memory task. *Consciousness and cognition, 36*, 61-74.

Rizzolatti, G. (1994). Nonconscious motor images. *Behavioral and brain sciences, 17*(02), 220-220.

Robinson, S., Goddard, L., Dritschel, B., Wisley, M., & Howlin, P. (2009). Executive functions in children with autism spectrum disorders. *Brain and cognition, 71*(3), 362-368.

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., & Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia, 42*(8), 1029-1040.

Russell, J. E. (1997). *Autism as an executive disorder*: Oxford University Press.

Schifter, C. C., & Cipollone, M. (2015). Constructivism vs Constructionism: Implications for Minecraft and Classroom Implementation. In P. Isaías, M. Spector, D.

Ifenthaler & D. G. Sampson (Eds.), *E-Learning Systems, Environments and Approaches: Theory and Implementation*. Switzerland: Springer.

Schwartz, D. M. (2014). Breaking Through Barriers: Using Technology to Address Executive Function Weaknesses and Improve Student Achievement. *Applied Neuropsychology: Child, 3*(3), 173-181. doi: 10.1080/21622965.2013.875296

Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal Society B: Biological Sciences, 298*(1089), 199-209.

Simon, H. A. (1975). The functional equivalence of problem solving skills. *Cognitive psychology, 7*(2), 268-288.

Spence, I., & Feng, J. (2010). Video games and spatial cognition. *Review of General Psychology, 14*(2), 92.

Spiegel, M. A., Koester, D., & Schack, T. (2013). The functional role of working memory in the (re-) planning and execution of grasping movements. *Journal of Experimental Psychology: Human Perception and Performance, 39*(5), 1326.

Stager, G. S. (2016). Seymour Papert (1928-2016). *Nature, 537*(7620), 308-308.

Staiano, A. E., Abraham, A. A., & Calvert, S. L. (2012). Competitive versus cooperative exergame play for African American adolescents' executive function skills: short-term effects in a long-term training intervention. *Developmental Psychology, 48*(2), 337.

Streib, J., Ayala, M., & Wixted, C. (2016). Benign Inequality: Frames of Poverty and Social Class Inequality in Children's Movies. *Journal of Poverty*, 1-19.

Strick, P. L., Dum, R. P., & Fiez, J. A. (2009). Cerebellum and nonmotor function. *Annual review of neuroscience, 32*, 413-434.

Takeuchi, L. M., & Vaala, S. (2014). Level up learning: A national survey on teaching with digital games. New York: The Joan Ganz Cooney Center at Sesame Workshop.

Thagard, P., & Aubie, B. (2008). Emotional consciousness: A neural model of how cognitive appraisal and somatic perception interact to produce qualitative experience. *Consciousness and cognition, 17*(3), 811-834.

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental science, 12*(1), 106-113.

Turk, M. (2014). Multimodal interaction: A review. *Pattern Recognition Letters, 36*, 189-195.

Unnithan, V. B., Houser, W., & Fernhall, B. (2005). Evaluation of the energy cost of playing a dance simulation video game in overweight and non-overweight children and adolescents. *International Journal of Sports Medicine, 26*, 1-11.

Unterrainer, J. M., Kaller, C. P., Loosli, S. V., Heinze, K., Ruh, N., Paschke-Müller, M., . . . Rahm, B. (2015). Looking ahead from age 6 to 13: A deeper insight into the development of planning ability. *British Journal of Psychology, 106*(1), 46-67.

van de Sande, E., Segers, E., & Verhoeven, L. (2015). The role of executive control in young children's serious gaming behavior. *Computers & Education, 82*, 432-441.

van Dijk, E. M., Lingnau, A., & Kockelkorn, H. (2012). *Measuring enjoyment of an interactive museum experience.* Paper presented at the Proceedings of the 14th ACM international conference on Multimodal interaction.

Ward, G., & Morris, R. (2005). *The Cognitive Psychology of Planning.* New York: Taylor & Francis.

Wechsler, D., & Hsiao-pin, C. (2011). *WASI-II: Wechsler abbreviated scale of intelligence*: Pearson.

Wickham, H. (2009). ggplot2: Elegant Graphics for Data Analysis: Springer-Verlag, New York. Retrieved from http://ggplot2.org

Wickham, H. (2011). The Split-Apply-Combine Strategy for Data Analysis. *Journal of Statistical Software, 40*(1), 1-29.

Wikipedia. (2016). Dance Dance Revolution. from https://en.wikipedia.org/wiki/Dance_Dance_Revolution

Willner, P., Bailey, R., Parry, R., & Dymond, S. (2010). Evaluation of executive functioning in people with intellectual disabilities. *Journal of Intellectual Disability Research, 54*(4), 366-379.

Wilson, B. A. (1993). Ecological validity of neuropsychological assessment: Do neuropsychological indexes predict performance in everyday activities? *Applied and Preventive Psychology, 2*(4), 209-215.

Wilson, B. N., Kaplan, B. J., Crawford, S. G., & Roberts, G. (2009). Psychometric Properties of the Revised Developmental Coordination Disorder Questionnaire. *Physical & Occupational Therapy in Pediatrics, 29*(2), 182-202.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*(4), 625-636.

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and virtual environments, 7*(3), 225-240.

Wong, D., Maybery, M., Bishop, D., Maley, A., & Hallmayer, J. (2006). Profiles of executive function in parents and siblings of individuals with autism spectrum disorders. *Genes, Brain and Behavior, 5*(8), 561-576.

Yang, T., Gathercole, S. E., & Allen, R. J. (2014). Benefit of enactment over oral repetition of verbal instruction does not require additional working memory during encoding. *Psychonomic Bulletin & Review, 21*(1), 186-192.

Zelazo, P. D. (2006). The dimensional change card sort (DCCS): A method of assessing executive function in children. *Nature Protocols, 1*(1), 297-301.

Zhang, W. (2015). Learning variables, in-class laptop multitasking and academic performance: A path analysis. *Computers & Education, 81*, 82-88.