Access to Eye-Gaze Control Technology for Children with Cerebral Palsy

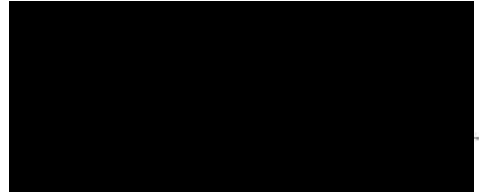**Tom Griffiths**

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Submitted for the award of PhD,
Research Degree in Language and Cognition

Declaration

I, Tom Griffiths, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

I'm not trying to prove anything, by the way.

I'm a scientist and I know what constitutes proof.

But the reason I call myself by my childhood name is to remind myself that a scientist must also be absolutely like a child. If he sees a thing, he must say that he sees it, whether it was what he thought he was going to see or not.

See first, think later, then test.

But always see first.

Otherwise you will only see what you were expecting.

Most scientists forget that.

"Wonko the Sane"
So Long, and Thanks for All the Fish
Douglas Adams (1952 – 2001)

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And also, I suppose, to Nelson who was an OK study buddy.

Abstract

Children with cerebral palsy (CP), whose disability may limit speech production and motor skills, are often considered good candidates for the use of eye-gaze technology to access communication, learning and play. At present, little is known about the skills needed to control this technology, which can make it difficult for clinicians to make decisions, or to manage expectations around progress. This is further complicated by the emergence of "teaching" software packages, claiming to improve basic skills such as cause and effect.

Children with CP are known to be at a higher risk of vision disorders, including those related to functional vision – how a child functions in vision related activities. These skills (in particular fixation and gaze switching) are similar to those required to make use of eye-gaze technology, so are likely to impact on children's performance.

This thesis uses typically developing children to provide baseline information and to observe how they respond to tasks which were incrementally lowered in terms of cognitive demand. Over three rounds of experiments a pattern emerged that children aged <24 months were unable to make any purposeful use of the technology and children >32 months were able to use it with only minimal instruction. The impact of teaching on performance was also investigated in this section of the study.

A group of children with CP were recruited to investigate the most effective way of assessing functional vision skills in this group, with results indicating behavioural measures were most effective.

A final study with children with CP used the activities above to look at the performance of this group on eye-gaze tasks. Results suggested good functional gaze control skills were related to better performance on a novel eye-gaze task. The findings suggest that some children may be at a "developmental advantage" if their functional vision and cognitive skills are more developed.

Impact Statement

Eye-gaze control refers to a group of technologies that allow interactions with a computer, communication aid or other assistive technology system using only the movement and rest of the users' gaze. This is a technology that is often considered for children with cerebral palsy (CP). At present, research in the field is sparse and clinicians lack robust evidence on which to base clinical decisions. In particular, there is a lack of understanding about how the technology is best introduced to developmentally younger children with CP.

This technology has cost implications, both in terms of its initial purchase and in the time spent by clinicians, families and educators supporting it. In recent years a plethora of "training" software packages have made the technology highly alluring to families, with claims that children can follow a "learning curve" from cause and effect and error-free play, all the way to purposeful control of a computer.

This work has relevance to a range of academic disciplines including child development and disability, language and cognition. In a field where published literature is scarce, this work may provide a starting point for future research by academics from disciplines such as speech and language therapy, occupational therapy and rehabilitation. It may also form part of future curricula for these groups. Elements of the methodology, particularly those related to testing vision in children with CP can also be helpful to future researchers. Suggestions for further research may inform future research applications by the author and others.

Whilst sections of this work have been presented at national and international conferences already, further dissemination in academic journals and at upcoming conferences is planned. The work has potential to inform practice both nationally and internationally by contributing to a growing programme of work on eye-gaze and functional vision at UCL and other partner institutions. It is the author's intention to continue this work, expanding on several elements of the methodology and on the ideas for future study.

Outside of academia, the work presented here has clinical implications for how decisions about eye-gaze technology are made and expectations around its use are managed. It includes practical and easily deployed methods for clinicians to obtain helpful information with which to support their decisions. The work therefore has potential to save money for public and third sector organisations tasked with supplying such technologies, particularly

those working in the fields of augmentative and alternative communication (AAC) and computer access. For children and families, the work has the potential to improve quality of life by ensuring that time and resources are directed where they will best support children. Commercially, the work may guide the development of future software packages for eye-gaze technology which may provide better information on the development of children's skills.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

For people with disabilities, access to assistive technology can provide a means to enhance participation, interaction, involvement and wellbeing (Chantry & Dunford, 2010; Delarosa et al., 2012; Light & McNaughton, 2013) and enable them to live healthy, productive, independent and dignified lives; participating in education, work and community (World Health Organization, 2016). For the group of children with movement disorders, access to computer technology can provide a means by which they can engage with communication, learning, play and leisure opportunities (Griffiths & Price, 2011).

Where these children are unable to use conventional means of controlling a computer (keyboard, mouse or touchscreen) a number of alternative "access methods" are available to clinicians. Amongst this array of tools, eye-gaze technology – a means by which a user can control a computer using only the movement and rest of their gaze – has seen a dramatic rise in interest and provision over the past decade (Karlsson et al., 2019; Wilkinson & Mitchell, 2014). However, in common with many other access methods, the skills needed to make best use of the technology are poorly understood, leaving clinicians with little evidence to support their decision-making or guide their interventions (Hoppestad, 2007; Karlsson, Allsop, Dee-Price, & Wallen, 2018). In practice, this can lead to children being given technology that they may be unable to use effectively (Light & McNaughton, 2013), with parents' expectations raised by the hope that the technology will "unlock" hitherto unrecognised potential or by claims that training programmes and software packages will lead to gains in performance. Similarly, clinicians and educators may propose the use of skill-building software and support sustained practice with the technology in the hope that this may lead to increases in performance and ability, although to date little evidence exists to guide such interventions (Borgestig, Sandqvist, Ahlsten, Falkmer, & Hemmingsson, 2016; Karlsson, Allsop, Dee-Price, & Wallen, 2018; Karlsson et al., 2020, submitted for publication).

This thesis explores the underlying skills which may contribute to better outcomes for children being considered for eye-gaze access technology. In doing so, this work highlights how assessment and understanding of these skills might help guide clinicians in decision making and in managing the expectations of families and those working with this group of children. The challenges which present in teaching the use of this technology are also

discussed and investigated, with practical recommendations made for how assessments might be carried out and how interventions can be effectively delivered.

1.1 Assistive Technology

Alternative computer access methods such as eye-gaze technology sit within the broad range of devices and systems available to support people with disabilities, which are often referred to as assistive technology (AT). A useful definition of AT is found in the United States Assistive Technology Act of 1998:

"[any] product, device, or equipment, whether acquired commercially, modified or customized, that is used to maintain, increase, or improve the functional capabilities of individuals with disabilities"

(United States Government, 1998)

The need for better provision and understanding of AT equipment and interventions is recognised worldwide, with Article 32 of the United Nations Convention on the Rights of Persons with Disabilities requiring governments to ensure the AT needs of citizens with disabilities are met (United Nations, 2006). However, a recent report from the World Health Organization emphasises that there are still significant gaps in provision; an estimated one billion people worldwide in need of some form of AT, but only one in ten has access to the appropriate services and technology (World Health Organization, 2011). Reasons for this under-provision include lack of funding, difficulties with the availability of products and technologies, lack of public awareness and the need for more trained or specialised personnel (World Health Organization, 2011).

The need in the global field of AT is therefore to reduce costs of equipment and provision, ensuring that services and interventions are provided for those who need them. Ensuring that equipment is appropriately provided and supported is an important part of maximising how it will be used to provide the maximum benefit to the individual user and the best return on investment for funders. Appropriate provision also minimises the rate of abandonment (J. M. Johnson, Inglebret, Jones, & Ray, 2006; McDonald, Harris, Price, & Jolleff, 2008; Rackensperger, Krezman, McNaughton, Williams, & D'Silva, 2005), meaning that the technology remains in use by those who need it most.

As a result of the above report, the World Health Organization made a commitment to improving understanding, awareness and use of assistive technology – convening an initiative entitled the Global Cooperation on Assistive Technology (GATE). The first publication from this project was the Priority Assistive Product List (World Health Organization, 2016). This list of fifty AT products was chosen by the GATE Initiative on the basis of widespread need and impact on a person's life. The list contains several alternative methods of accessing and controlling a computer, including keyboard and mouse emulation hardware and software such as eye-gaze technology. The list also includes systems, devices and technologies to support the expressive communication of people with limited or no functional speech. Inclusion of these technologies highlight their importance to people with disabilities and the need to encourage their use and understanding by assistive technology professionals.

1.2 Augmentative and Alternative Communication

A common reason for which children with movement disorders such as cerebral palsy (CP) might require access to a computer, is to make use of "augmentative and alternative communication" (AAC). The American Speech-Language-Hearing Association (ASHA) defines AAC as a variety of techniques and tools, including picture communication boards, line drawings, speech-generating devices (SGDs), tangible objects, manual signs, gestures, and finger spelling, to help the individual express thoughts, wants and needs, feelings, and ideas (American Speech-Language-Hearing Association, 2017). Whilst this definition captures the full breadth of AAC strategies, the term AAC is most commonly used to refer to formal systems of language representation which are explicitly introduced and taught (M. Clarke, Price, & Griffiths, 2016). The broadest definitions of AAC would also include support for understanding language, such receptive support strategies fall outside the scope of this work and the term AAC is used throughout this thesis to refer only to strategies to support expressive communication.

The group of children with CP who are considered candidates for AAC will likely have a poor prognosis for speech development and face significant barriers to their communication with others (Pennington, Goldbart, & Marshall, 2004). These barriers can include difficulties using clear speech to convey messages, reduced ability to use manual sign, gesture and pointing, dependence on familiar partners to interpret vocalisations or speech approximations and limited opportunities for flexible communication and self-expression (M. Clarke et al., 2016;

Griffiths & Addison, 2017). Children who experience these limitations may be introduced to AAC equipment, techniques and strategies to support their expressive communication.

1.2.1 Classification of AAC Systems

It has been observed (Baxter, Enderby, Evans, & Judge, 2012b) that there is a lack of clarity in the field of AAC regarding the terminology used to describe and categorise equipment, devices and strategies. One commonly used taxonomy (visualised in Figure 1) categorises AAC by the amount and complexity of additional support required. In this taxonomy, AAC falls broadly into two categories: aided and unaided. Unaided or "no-tech" techniques rely on the user's body to transmit messages, using facial expression, gesture, and / or sign languages. Aided techniques require an additional device or means of conveying a message.
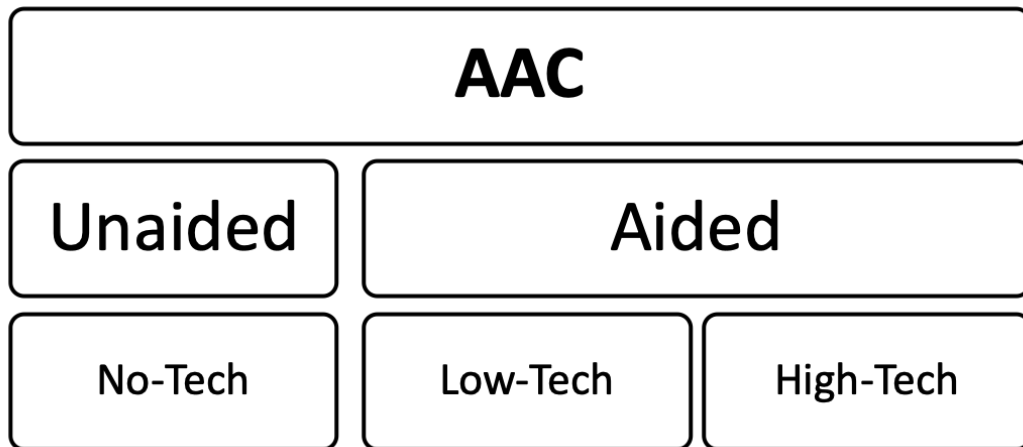
Figure 1 - Basic taxonomy of AAC systems and techniques

Aided AAC techniques are often divided into two subsets: either "low-tech" or "high-tech". Low-tech systems may include the use of alphabet boards, printed materials with written words or graphic symbols, photographs or communication books. A high-tech communication aid is generally considered to be one that is powered by battery or mains power, and typically one which contains a microprocessor. The distinction between low- and high-tech is not intended to reflect the complexity of the communication, but rather the complexity of the technology. For this reason, synonyms such as "powered" and "non-powered" are sometimes used (Baxter et al., 2012b). Nor does this taxonomy seek to imply a hierarchy of these methods, with best-practice guidelines encouraging the use of both high- and low-tech resources for communicators at all skill levels.

High-tech devices can include bespoke-designed computer systems, which are commonly referred to either as speech generating devices (SGDs) or voice output communication aids (VOCAs). In the more recent past, the definition of high-tech AAC has also come to encompass voice output software installed on commercially available laptop or tablet computers. This "mainstreaming" of AAC and the corresponding increase in the number of functions that one device can fulfil has led to a shift in the way in which AAC is provided.

1.2.2 High-Tech AAC and the Advent of the "Multi-Functional" Device

In 2011 Griffiths and Price published a discussion paper which summarised the changing applications of this technology, where one "multi-functional" device with different software packages could now support children with access to communication, learning and play (Griffiths & Price, 2011). This paper foregrounded the importance of valuing the perspectives and goals of all stakeholders in the assistive technology selection process and recognising the distinctions between the activities and occupations that technology has the potential to support. The paper discussed the risk that too tight a focus on the use of technology to support communication might lead to missed opportunities in other areas such as play; which may in turn result in frustration and potential abandonment of a device that could have fulfilled an alternative role for the child. The paper highlighted the need for clinicians to keep in mind all the potential applications of technology for a child and not to pursue use of technology for its own sake: ensuring that goals for the use of the technology were clearly set and that successful outcomes in all three areas of technology use were valued.

In the time since this paper was published, the situation has become still more complex for clinicians. Multi-functional devices are now the market leaders, with dedicated SGDs in the relative minority and an increased recognition that technology can be used to support communication and interaction at all levels and through means other than the selection of cells from a fixed "grid" to form a message (Koch Fager, Fried-Oken, Jakobs, & Beukelman, 2019; Light & McNaughton, 2012, 2013; Waller, 2019; Wilkinson & Light, 2014). Studies have highlighted the communicative potential of using a computer to play interactive games (Smith, 2019), or to share experiences by means of photos and video content.

Concurrent with this, manufacturers of AAC hardware and software have increased their focus on early or emergent AAC users, as well as those who need support for learning, play

and leisure activities. This shift has seen a proliferation of software and tools to support clinicians in introducing communication and computer use, or for "teaching" children basic communication skills or the operational skills needed to control the device. An example of this is the increased inclusion in many AAC software packages of interactive games or activities which support children in learning to use the technology, and the increased number of software packages targeted specifically at "teaching" children to use eye-gaze technology.

1.2.3 Early Intervention and Presumed Competence

In the early years of AAC as a clinical and research discipline, many children and young people with disabilities were excluded from intervention due to their perceived or assessed levels of cognition or development (Cress & Marvin, 2003; Romski & Sevcik, 1988, 1993). Often, provision of AAC was not considered for children whose developmental levels or sensorimotor skills were below those of typically developing children beginning to develop language (Hourcade, Everhart Pilotte, West, & Parette, 2004). This more impairment-focused "candidacy model" paradigm effectively imposed a series of "prerequisites" which were required to be met before AAC would be considered (Wilkinson & Hennig, 2007). Effectively, there was a requirement on users to prove that they had certain skills before the technology would be provided. This model of service delivery often cast assistive technology professionals in the unwelcome role of "gatekeepers" (Kangas & Lloyd, 1988; Ratcliff & Beukelman, 1995).

In more recent years, however, research and technological developments in AAC and access have opened up these interventions to a great many more children. Concurrent with the more general shift in the field of assistive technology from the medical model to a more "social model" of service delivery (Hoppestad, 2007), it is now more generally acknowledged that children who lack a means of expressive language may be at a developmental disadvantage (Cress & Marvin, 2003; Romski & Sevcik, 2005). Furthermore, with the ever-increasing ubiquity of computer technology in all areas of life, children are at risk of reduced participation if they are not able to access a computer (Chantry & Dunford, 2010). These children may be at an increased risk of difficulties in developing functional communication, literacy, social participation and basic language skills (Drager, Light, & McNaughton, 2010). It has also been suggested that, since children with severe and complex sensorimotor disabilities cannot demonstrate their skills without a communication system, it is unreasonable to expect the attainment of a certain cognitive or language level before such

a system is provided (Romski & Sevcik, 2005). A strategy of early intervention became more prevalent in the AAC community.

The challenge for the field of AAC has become how to ensure that children are provided with the support they need at an early age, whilst ensuring that expectations of parents and professionals are kept clear and realistic. The shift away from a way of thinking based on prerequisites should not mean that understanding of a child's profile of strengths and difficulties is any less important. The value of careful observation and assessment to support decision-making cannot be underestimated when selecting and designing an AAC or access system for a child (Dietz, Quach, Lund, & McKelvey, 2012; Jones, Jolleff, McConachie, & Wisbeach, 1990).

Concurrent with the recognition of the importance of early intervention, the field of AAC has seen a growth in a way of thinking known as "presumed competence". First articulated in the mid 1980s, this theory is based on making the "least dangerous assumption" about a child's abilities; in essence advocating that, if cognition or other skills cannot be accurately assessed, then it is better or less damaging to overestimate a child's ability than to underestimate it (Donnellan, 1984). Proponents of this way of thinking feel that the approach ensures the dignity of people with disabilities and provides those supporting them with a starting point of optimism, which will encourage harder work and a more positive experience. Critics have pointed out that, since there exist no published studies supporting the idea of presumed competence, its use as a starting point for interventions such as communication or access is unwarranted (Travers & Ayres, 2015). Further, the presumption of competence is likely to lead to a confirmation bias, where evidence is sought to back up an opinion or presumption, with evidence that contradicts it explained away or ignored. Presuming competence could be seen as antithetical to the idea of careful assessment and observation, since it is based on presumptions of individual clinicians and treats many of the skills that may be crucial to progress as "unknowable" or "unassessable". This in turn may lead to the setting of unrealistic expectations and the failure to value the real achievements made by children.

As will be discussed in greater detail later (Chapter 6), careful adaptation of tests and the use of structured informal assessment by professionals can provide insight into a child's profile of strengths and difficulties that can influence the selection of interventions, including the

choice of assistive technologies (Alant & Casey, 2005; Gumley, Price, & Griffiths, 2011; Stadskleiv, 2020). In order to better understand how to support these children, it is necessary to provide ways in which they can show their levels of understanding. A growing body of evidence (examined in greater detail in Chapters 2 and 5) supports the use of assistive technology to provide methods of assessment that minimise the physical demands some assessments place on children and that offer non-verbal ways of assessing early cognitive skills (Cook, Adams, Volden, Harbottle, & Harbottle, 2011; Geytenbeek, Vermeulen, Becher, & Oostrom, 2015). This thesis seeks to contribute to that discussion.

This thesis takes as its starting point the core principle that no child should be excluded from access to assistive technology intervention, nor to communication, education, play and leisure through control of a computer. However, these interventions and the support provided to these children should be pitched at a level which is appropriate to the individual's skills, so that parents, clinicians, educators and other stakeholders might best understand the child's profile of strengths and needs (Gosnell, Costello, & Shane, 2011; Griffiths & Price, 2011). In order to correctly match the individual with appropriate intervention, and to manage the expectations of those supporting them, a solid understanding of the strengths and needs of each individual is required. This will, in turn, allow each child to maximise their abilities and provide recognition of their progress and achievements.

1.3 Motivation for Research

The questions addressed in this thesis have their roots in the 2011 paper by Griffiths and Price and were arrived at as a result of the clinical experience of the author, whilst working in a specialist AAC service as part of a multidisciplinary team. In this setting, children with a range of disabilities were referred for assessment and provision (where appropriate) of AAC systems and strategies. With the advent of eye-gaze technology, an increase was noted in the number of children being referred to the service with requests by referrers or parents for an "eye-gaze communication aid", or with reports that the children had trialled the technology with great success. Often it was noted that these children had trialled games or activities from the aforementioned teaching and training packages. On closer inspection, the skills demonstrated appeared to be developmentally early: fixation on a single target, orientation of the eyes to a motivating video or moving the eyes around the screen area to produce animation wherever the gaze point registered. However, because many of the

training packages included a continuum of learning that culminated in communication (see Chapter 5), and because all were published by established suppliers of communication aid software, a perception seemed to be emerging that the early stages of these software packages were a "first step" towards successful use of a formal AAC system. Further, the use of animation, sound and video generated wherever the child looked could make even very early gaze behaviours seem highly significant.

This perception presented several challenges to clinicians working in the field of AAC. Firstly, the access method ("eye-gaze") and the activity or task ("communication") appeared to be becoming increasingly conflated. Whilst it is an established principle of AAC intervention that successful aided communication includes successful use of the means of access and selection (Light, 1989), the use of software packages such as these that focused only on use of the access method in their early stages appeared contrary to the prevailing evidence that skills should be practiced in the context of functional activities to maximise outcomes (Griffiths & Addison, 2017).

Secondly, clinicians working in the field of AAC lack evidence on which to base decisions about whether or not to recommend eye-gaze technology. Several researchers have highlighted this (Hoppestad, 2007; Myrden, Schudlo, Weyand, Zeyl, & Chau, 2014; Stokes & Roden, 2017), most notably Karlsson and colleagues (2018) who conducted a systematic review of the evidence for the use of this technology with both children and adults in 2018, concluding that "Research regarding the effectiveness of eye-gaze control technology […] on communication outcomes, participation, quality of life and self-esteem in children, adolescents and adults with cerebral palsy and significant physical disability is sparse" (Karlsson et al., 2018, p. 497). The lack of good quality evidence on which to base decision-making increases the risk that technology will be inappropriately prescribed. Further, the "no-fail" approach taken by the early stages of many eye-gaze training packages made discussions with parents and professionals challenging, since it was not possible to be sure whether sustained use of these activities would lead to gains in performance. Increasingly, the training packages were filling a "gap" in the understanding of this technology, with clinicians under pressure to provide expensive technology and invest time in an intervention that had, at best, an uncertain outcome.

Thirdly, children would often be referred with requests for eye-gaze technology with no reports made of their vision or visual ability, and with little report of their cognitive skills (Sargent, Clarke, Price, Griffiths, & Swettenham, 2013; Sargent, Griffiths, & Bates, 2017). Often, these would be accompanied by reports of a child's "surprising" performance with the technology, perhaps demonstrating skills that had not previously been realised. In some cases, these skills were difficult to demonstrate in the context of an assessment or beyond the specific activities included in the training software. This suggested that the software packages, or the way in which they are being used, may be over-estimating the skills of some children, or that families and professionals may have misunderstood the nature of those skills. A good example of this is the number of "cause and effect" activities included in the early stages of many training packages, many of which do not in isolation provide good evidence that this skill has been established. These concerns are discussed in more detail in the following chapters. The importance of robust assessment is a well-established principle in AAC and other assistive technologies (M. Clarke et al., 2016; Jones et al., 1990; Scherer, Jutai, Fuhrer, Demers, & Deruyter, 2007; Steel, Gelderblom, & de Witte, 2011), as will be demonstrated in the following sections of this chapter. The risk that the reports of software packages might be seen as a "proxy" or replacement for specialist assessment, particularly when making requests for funding, was another key motivator for this research.

1.4 Research Aims

This thesis takes as its central aim the exploration of factors that may impact on making purposeful use of eye-gaze technology in young children with CP. Whilst it is not the intention of this work to impose prerequisites on the provision of this technology, the research investigates whether certain factors might be effective predictors of performance with eye-gaze technology. In particular, the work investigates the relationship between cognitive development and the control of an eye-gaze system, in both typically developing children and children with CP. Allied to this, it is proposed that the non-physical nature of the interaction between a person and an eye-gaze control device, and the lack of a clear causal relationship between eye movements and the resulting actions on screen, will mean eye-gaze technology is harder for children to intuitively learn. One rationale for the work is that cause and effect in particular is crucial to successful use of eye-gaze technology, but that it may present differently when applied to eye-gaze technology.

Also underpinning this work is the theory that eye-gaze technology is harder to teach than other access methods; presenting specific challenges to those supporting children to use it. Where other access methods can be demonstrated or modelled when they are first introduced, this is much harder with eye-gaze technology. The process of teaching children to use the technology may therefore be more reliant on spoken instruction and feedback. It is proposed that this may present a challenge for the group of children with CP, who are more at risk of difficulties with receptive language and may not have sufficient understanding of language to fully comprehend the instructions being given to them.

Finally, this work also explores the impact of "functional gaze control" skills on the purposeful control of an eye-gaze technology system. Many of these skills (fixation on a target, transferring gaze between multiple targets, following a moving target) are similar to the skills targeted for development by eye-gaze training software. It seems likely that children who have difficulties demonstrating these skills in observation or behavioural assessment will also have difficulties using them to access eye-gaze technology. Previous research has shown that children with CP are at risk of damage to all aspects of the visual system (McCulloch et al., 2007; Venkateswaran & Shevell, 2008), including these functional gaze control skills (Atkinson & Braddick, 2012; Deramore Denver, Froude, Rosenbaum, Wilkes-Gillan, & Imms, 2016; Sargent et al., 2013) and it is therefore proposed that careful observation and discussion of these skills by clinicians and families may provide a useful insight into how children may perform with an eye-gaze system.

1.5 Significance of the Work

Previous sections have highlighted the sparsity of evidence around eye-gaze technology. This work seeks to provide clinicians with information on which to base decision-making, contributing to the growing body of literature focused on the assessment of children for this complex technology and how best this assessment process might be carried out (Karlsson et al., 2020, submitted for publication).

In terms of the clinical applications of this work, the outcomes of this research may help manage expectations around a technology that is very alluring and, in some cases, seen as a panacea. It is not the intention of this work to criticise the eye-gaze training packages discussed in the following chapters, but to encourage those using them to consider the task demands of the games, question the skills that are really being demonstrated, and to

examine the results and feedback they provide in the context of a child's overall development.

The experiments described in this thesis also seek to contribute to the discussion around how clinicians can best support use of eye-gaze technology in a way that does not take away the child's own independence or agency by making the tasks too easy or by "scaffolding" a child's performance to unrealistic levels.

1.6 Organisation of the Thesis and Research Questions

This thesis is laid out in four sections, across thirteen chapters, presenting the results of five rounds of experimental work. An outline of the thesis and a narrative account of the work are presented below.

1.6.1 Section One – Theoretical Basis

The first section sets out the theoretical constructs on which the research is based. Chapter 2 frames the concept of access and discusses the types and classifications of access technologies, as well as presenting a review of current literature on the topic. This chapter includes a general discussion of access to technology and summarises the assessment process followed by clinicians in selecting an access method for an individual. This chapter also introduces eye-gaze technology; presenting an overview of how it works, including an introduction to human eye physiology and how an eye tracker uses features of the eye to estimate gaze points. This chapter begins to frame the discussion of how eye-gaze technology might differ from other access methods in terms of the cognitive load and the different types of feedback it provides for the user. The chapter also explains the important distinction between "eye-gaze" and "eye tracking" technology and how each is used in the activities described in this thesis.

Chapter 3 describes the typical development of human vision, visual function, pointing and cause and effect. This chapter presents "timelines" for the development of vision and cause and effect in typical development and discusses briefly how these may develop differently in children with disabilities which restrict movement and participation.

Chapter 4 discusses cerebral palsy (CP) in greater detail, looking at the aetiology of the condition, its classification, prevalence and clinical description. The chapter places an

emphasis on the functional description of CP which underpins this work, describing the impact of CP on communication, posture, gross and fine motor control. Potential barriers and facilitators to computer access are discussed and some of the interventions commonly used to support this population are outlined.

In Chapter 5, the discussion turns to current issues in the use of eye-gaze technology, and in particular the gap between current research and clinical practice. The chapter also introduces some of the aspects of this technology which may make it harder for children to learn. Some of the challenges for those observing the performance of children learning to use it are also outlined here. The increasing number of eye-gaze "teaching and training" software packages is also discussed, outlining the types of activities they contain and the skills that they claim to measure.

Concluding the first section of this thesis, Chapter 6 discusses challenges in the assessment of children with severe motor disorders, limited expressive communication and cognitive impairment. Through this discussion, methodological decisions taken by the author in carrying out this work are explained and justified. This chapter presents the rationale for adapting several measures of language and cognition used throughout the experimental work and discusses some key principles in the design of the experiments that are used to test typically developing children and children with CP. This chapter also outlines the reasons for using typically developing children as research subjects in the development of the activities used to assess the skills of children with CP.

1.6.2 Section Two – Experimental Design

The second section of the thesis describes the development of experiments to assess eye-gaze performance in the clinical population of children with CP. This section focuses on analysing some of the key developmental skills which are crucial to the use of eye-gaze access technology, looking in more detail at the difference in the nature of cause and effect skills required to use an eye-gaze system and reporting on several iterations of experimental tasks seeking to engage more, developmentally younger children in using eye-gaze to gain insight into these skills. Chapter 7 presents the methodology and results of an exploratory study looking at typically developing children's performance using an eye-gaze control device to learn and complete a simple sequencing game. The task includes two learning phases, in which children were introduced to an "effective" and "ineffective" button in turn, and a test

condition where children were required to use this acquired knowledge to complete the task; inhibiting the ineffective button in favour of selecting the effective one. The research questions addressed in this chapter are:

1. At what developmental age can children apply knowledge of cause and effect to complete a simple game using an eye-gaze device?

2. What is the relationship between developmental age and performance on eye-gaze control in typically developing children?

The results suggest that children who scored at a developmental level below 24 months were not able to complete any part of the protocol, with a significant correlation existing between children's performance and their developmental age. Children aged above 32 months were able to use the device to complete all phases of the experiment. Associations were noted between children's ability to sustain engagement with the task and their performance, indicating that the development of attention may impact on learning to use an eye-gaze system.

Chapter 8 therefore discusses changes in experimental design intended to make the experiments more engaging and to investigate whether it was possible to reduce the developmental age at which children could engage with the activities. This included making the experiments more visually appealing and removing the sequencing elements of the previous trial. The research questions for this chapter are:

3. Do the changes made to the experimental design allow more, younger children (below 32 months) to engage with the task?

4. Does a learning effect exist as children become more familiar with the properties of the stimuli presented?

5. Can children who demonstrate sufficient engagement and sufficiently well-developed cause and effect skills to complete a game with highly motivating stimuli generalise these skills to similar, less "exciting" stimuli?

Results from this chapter provided further evidence of a significant correlation between children's developmental level (measured using their receptive language understanding) and the number of trials with which they engaged, with children who were able to engage with at least half of the experimental protocol being significantly older. Once again, children who completed the full experimental protocol all aged over 30 months. Another key observation was that no learning effect existed within the trials, with no significant increase in the percentage of children selecting the active button between the first and last trials.

For children who completed the full experimental protocol, further trials were conducted in which the highly salient visual targets were replaced with equivalent static pictures, akin to the graphic symbols used in high-tech AAC systems. These trials aimed to identify whether the skills learned could be generalised to new stimuli and the results demonstrated that children who completed the initial experiments were able to successfully generalise these skills to novel stimuli, with their ability to select the effective stimulus being similar across the moving and static stimuli. The results indicated that children who were able to complete the task with highly salient stimuli were able to generalise the use of that skill to an experiment where the stimuli were less "attention grabbing".

Chapter 9 explores whether actively teaching or coaching typically developing children had any impact on their performance with an eye-gaze system, given the absence of a learning or weak learning when no instruction or feedback was given. This chapter uses "causal language" instruction which, it is argued, is the best available way to support children in learning to use eye-gaze technology. The activities in this chapter were designed to compare typically developing children's performance with an eye-gaze task at three different points: with no training ("baseline"), during an instructive session with coaching and spoken feedback ("intervention"), and a final session to see whether the teaching had been retained ("post-intervention"). Changes were made to the design of the experiments, using pictures and videos of real people making social eye contact with the child in order to increase the likelihood that children would look to the stimuli. Children forming the participant group for this study had a lower mean age (28 months) than previous groups, although it was once again noted that the children who did not complete the whole protocol due to opting out or not engaging were at the younger end of the age range. The research questions addressed in this chapter are:

6. Can typically developing pre-school children learn to better use eye-gaze control technology after explicit teaching and instruction using causal language?

7. Do typically developing pre-school children perform better in cause and effect tasks when using touchscreen technology than when using eye-gaze control technology?

The results showed little or no differences in children's performance at baseline and post-intervention, although the majority of children showed an improvement in performance during the intervention phase. This indicates that this group of children were able to use immediate causal language instruction and feedback on performance to successfully complete the task, but that this did not transfer to consolidated gains in performance when this feedback was removed. These results suggest that explicit teaching and feedback during the learning of an eye-gaze task may have limited impact on children's overall improvement in their use of eye-gaze technology.

In this section of the study, children were also asked to complete the same task using a touchscreen, in order to provide a comparison between the use of eye-gaze technology and the use of an access method with which children are more familiar (Enderby et al 2013, Given et al 2014). An additional research question is therefore addressed in this chapter:

8. Will the likely performance disparity between performance on touchscreen and eye-gaze control tasks decrease after explicit teaching and instruction?

The children taking part in the study consistently performed better on tasks using the touchscreen. Observations of the children's behaviour during both the eye-gaze and touchscreen conditions suggests that children find touchscreens more accessible than eye-gaze: 38% of failed trials in the eye-gaze condition were caused by children touching the screen, with the frequency of this occurring not altered by whether they had completed the touchscreen condition first.

The findings of these three studies seem to suggest that there is something about the cause and effect skills needed for the use of eye-gaze technology which differs from the use of these skills for physical objects and events.

1.6.3 Section Three – Functional Gaze Control in Children with Cerebral Palsy

The third section of the thesis focuses on functional gaze control and its impact on the use of eye-gaze technology by children with CP. This section aims to examine the variation in functional gaze control skills in non-speaking children with four-limb CP and the impact of this variation on performance with an eye-gaze system.

Chapter 10 describes in detail what is meant by the terms "functional vision" and "functional gaze control", as well as discussing how these skills are assessed, observed and described. The ways in which such issues might impact on the use of eye-gaze technology are presented. This chapter sets up the assessment of these skills and proposes the investigation into whether they are best assessed using technology or behavioural observation.

Chapter 11 compares the use of eye tracking technology and behavioural assessment to observe and record the functional gaze control skills of children with CP. This chapter describes the design and implementation of experiments designed to elicit the key functional gaze control skills of fixation and gaze switching, both through eye tracking and behavioural measures. Some of the challenges in using an eye tracker with children with CP are discussed – principally those around calibration and data quality. The materials used in the behavioural tasks are described and the results of both are compared, again in terms of the number of children who engaged with each task, and their performance on both. The research questions addressed in this chapter are:

9. Are children with cerebral palsy able to calibrate an eye-tracking computer with enough precision to allow the gathering of reliable data on their eye movements?

10. Is an eye tracking computer a useful tool for collecting information on the functional gaze control skills of this group of children?

11. How do the same group of children perform on behavioural functional gaze control tasks?

12. What is the profile of functional gaze control skills in this group of children?

The conclusions are that calibration of an eye tracker to the accuracy required for research software is difficult in the population of children with CP. Even when calibration is achieved, difficulties with children's using the technology make the results unreliable. When compared to behavioural observation, it is noted that some children who were not able to calibrate the device were able to demonstrate good functional gaze control skills by other methods. It was therefore concluded that behavioural observation of functional gaze control skills is equally informative and more inclusive than the use of an eye tracker in this population of children. The chapter also highlights the considerable variability in the functional gaze control skills of children assessed using these measures, further highlighting the importance of testing these skills in this population.

1.6.4 Section Four – Final Experimental Work, Discussion and Conclusions

Chapter 12 presents the final round of experimental measures. This chapter investigates the performance of children with CP on the tasks developed in Section 2 and looks at the impact of their functional gaze control skills on this performance. As such, a group of children with CP were recruited and tested, using behavioural measures of functional gaze control and eye-gaze activities. Children's functional gaze control skills were screened as part of the background measures for this task and they were allocated to a group with either stronger or weaker skills. Each group then attempted the same experimental measures using eye-gaze control technology, in order to assess the impact of these skills on their performance. The following research questions are addressed in this chapter:

13. What is the relationship between functional vision skills and performance with eye-gaze technology in children with CP?

14. What is the relationship between developmental age and performance with eye-gaze technology in children with CP?

15. What impact does explicit teaching and prompting have on the performance of this group, and can any improvement in performance be retained?

The activities described in this chapter show that functional gaze control skills do indeed seem to impact on performance with an eye-gaze control device. Only children who were assessed as having stronger functional gaze control skills were able to complete the full

protocol and there was a noticeable difference in performance between these children and those whose functional gaze skills were weaker. Children with stronger functional gaze control skills who were younger than the 22-month level identified in the studies with typically developing children were able to perform better if they had previously had practice with eye-gaze technology. For children with poorer functional gaze control, prior experience did not appear to impact on their performance.

Chapter 13 concludes the thesis with discussion of the results, and the implications for clinical practice. Future areas for research are also proposed.

Chapter 2

Assistive Technology and Computer Access

2.1 Introduction

This chapter frames the concept of access to computer technology, providing an introduction to some of the frameworks and models that underpin this research and situating computer access within the context of the broader field of assistive technology. The following sections discuss some proposed models for assessment, setting out the importance of a robust understanding of a child's strengths and needs when considering any intervention using assistive technology. The barriers and solutions that impact on the selection and implementation of an access method will also be discussed and a summary of the assessment process that may be required to identify a suitable means of controlling a computer or augmentative or alternative communication (AAC) system is offered. The chapter concludes with an overview of eye-gaze technology.

2.2 Assistive Technology and the ICF Framework

For professionals considering the introduction of any assistive technology, including high-tech AAC systems, there are many factors to consider before an appropriate system is selected (Hersh & Johnson, 2008a; Jones et al., 1990; Scherer et al., 2007). A child's physical skills, cognition and sensory abilities can all impact on the selection of these systems, as can the environment and the levels of support available to them.

A useful model for conceptualising disability in assessment and research is the *International Classification of Functioning, Disability and Health* (ICF, World Health Organisation, 2001). The ICF is designed to promote a universal language to describe aspects of people's functioning and health (Fried-Oken & Granlund, 2012) and the impact of their environment. At its core is the bio-psychosocial framework (Figure 2) which models health and disability as the result of the interaction between health condition and contextual factors (World Health Organisation, 2001). The framework is made up of inter-related components or domains, the interactions between which can be used to describe a person's functional ability and identify any barriers they may face to their participation in life situations.
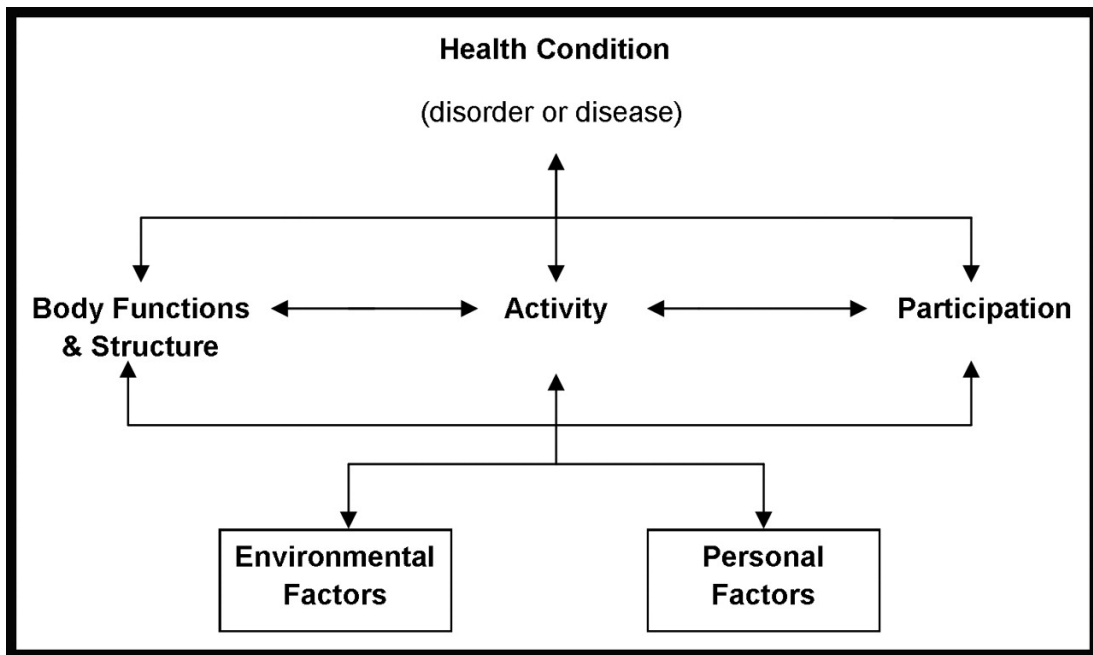
Figure 2 - Model of functioning and disability, showing the interactions between components of the ICF (WHO, 2001)

The ICF promotes a view of disability which extends beyond the medical model of diagnoses, symptomology and treatments, and encompasses elements of a person's support network, their environment and social systems, any assistive devices they may need or use, as well as the range of activities and occupations in which they may be involved. This bio-psychosocial model has resulted in a shift in thinking away from medical descriptions of impairment and towards functional descriptions intended to complement diagnosis and provide a more complete picture of an individual's abilities and the context in which they function (Griffiths & Addison, 2017).

Because of its stated focus on creating a common language for the description of functioning and disability, the ICF is widely used around the world across the domains of research and clinical practice (Cerniauskaite et al., 2011). It has been used as a framework for describing research participants (Pennington, Marshall, & Goldbart, 2007), as a theoretical basis for developing tools and scales (Fried-Oken & Granlund, 2012; Pennington et al., 2013; Steel et al., 2011), as an aid to clinical decision-making (Griffiths & Addison, 2017) and to guide policy-making, service delivery and commissioning (Department for Education, 2013).

For assistive technology, the ICF represents a helpful model for conceptualising a person's abilities and the barriers and facilitators to their use of a particular technology. The model

foregrounds participation (defined within the ICF as "involvement in a life situation") as an outcome for interventions such as the provision of assistive technology. The framework encourages clinicians to consider not only interventions targeted at the level of body functions and structure, but also environmental interventions such as support worker training or the establishment of environments that offer better support and access for people with disabilities (Anderson, Balandin, & Stancliffe, 2016; Baxter, Enderby, Evans, & Judge, 2012a; Cowan & Najafi, 2019; Kent-Walsh & McNaughton, 2005; Sullivan & Lewis, 2000).

2.2.1 Computer Use in Disability – Enabling Participation

The ICF framework represents a starting point for classifying and conceptualising disability, functioning and support. In this framework, assistive technology is considered an environmental factor under the general heading of Products and Technology. Assistive technology in the context of the ICF model is therefore a contextual factor with the potential to facilitate participation (Griffiths & Price, 2011; Steel et al., 2011).

The impairments of body functions and structure (which include both physiological and psychological functions) which occur in complex neurological disabilities such as CP can limit children's participation and involvement. However, for children with such descriptions, the use of computer technology is often considered as a way to increase the range of activities in which they can participate, to promote increased autonomy and to narrow the gap in participation between them and their typically developing peers.

Chantry and Dunford conducted a systematic review of the literature on computer use by children with complex disabilities, seeking to explore whether the use of computers and computer-based assistive technologies enhances the participation and range of occupations in which these children engage (Chantry & Dunford, 2010). The 27 papers identified in the search were appraised and categorised using the well-established Occupational Performance Model (Australia) (Chapparo & Ranka, 1997), which classifies occupations into four areas: self-maintenance; productivity / school; leisure / play; and rest. Whilst the final category (rest) was excluded because the study focused on active engagement and participation, the researchers found evidence supporting the use of computers by children with CP in the other three categories of occupation; broadly supporting the recommendation

that computer assistive technologies should be considered in a range of contexts to enhance the participation of these children in a variety of occupations (Chantry & Dunford, 2010).

Of particular relevance to the current project was the strength of the literature supporting the use of computers in education, communication and play. Included studies highlighted that computer use by this group of children offered ways for children to engage in play as an equal partner, achieve greater autonomy and independence, reveal their learning potential, engage in social interaction and take part in learning and rehabilitation in a "safe" environment where they could make mistakes without worrying about the consequences of their errors. Provision of computer technology was found to promote cognitive development, increased engagement in play and better social interaction.

2.3 Models Specific to Assistive Technology

Whilst the ICF can help to describe the impact of any assistive technology and the interactions on which its successful use relies, several authors have pointed out that it is a relatively "blunt instrument" when it comes to describing the features of the technology itself, how these interact with particular features of a person's disability, or the outcomes of specific interventions (Bauer, Elsaesser, & Arthanat, 2011; Hersh & Johnson, 2008a, 2008b; Steel et al., 2011). Several other models that describe the technology and its impact have been developed, many using the ICF as their foundation, and the following sections describe two of these that have influenced the design of the work reported in this thesis.

2.3.1 Human Activity and Assistive Technology (HAAT)

The Human Activity Assistive Technology (HAAT) model, first proposed by Cook and Hussey in 1995 and updated on several occasions since, takes a human performance approach to the provision of assistive technology (Cook & Hussey, 1995; Cook, Polgar, & Hussey, 2014). The HAAT model places focus on the roles and applications of assistive technology: acting as a useful framework to describe the uses that technology can have for a person with disabilities. The model is traditionally represented as a three-part circle representing the key components of the person, the activity and the assistive technology, set within a square representing the context (Figure 3). This model treats the interactions between these components as a system that is dynamic and can vary with task, time and location: with the boundaries between sections adjusting, depending on the individual needs of the user. For a person with moderate disability, the circle may be equally divided as shown in Figure 3,

whereas for a person with more severe disability, the Assistive Technology component may be larger, expanding to fill part of the Human section. This concept is known as "function allocation" and represents the idea that individuals will need different levels of support from their assistive technology, depending on their abilities and the task.
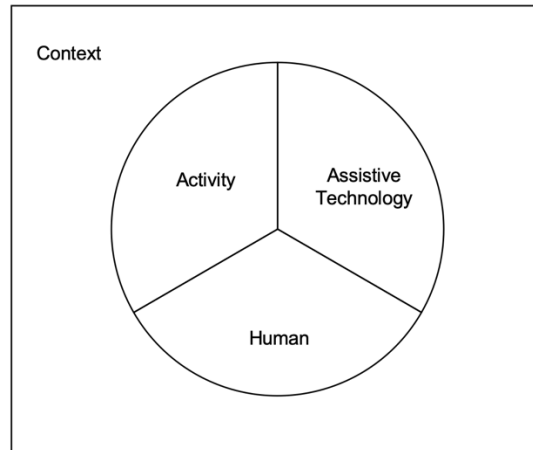
Figure 3 - The basic Human Activity Assistive Technology (HAAT) Model
(Cook & Hussey, 1995)

Taking computer access as an example, the traditional model sees the input functions (pressing a keyboard key, moving and clicking the mouse) allocated exclusively to the user – the Human section of the model. For a user with a movement disorder that limits the accuracy of upper limb movement, a larger keyboard might need to be provided or the use of switch scanning considered, where the locating of items is handled by the computer. If this person has an additional visual impairment then high contrast hardware and software or a screen reader might be required. In both cases, the boundary between Human and Assistive Technology shifts to make the latter component larger, as more functions involved in the Activity are allocated to it. The Human component of the system is conversely allocated fewer functions, with the technology supporting those that the user is unable to complete independently. The HAAT model is also designed to change in a similar way according to time and location, reflecting that a person can need more support from their assistive technology at one time than at another – perhaps to counteract the effects of fatigue – or in familiar versus unfamiliar environments. In the context of the HAAT model, the Context component includes both the social frameworks and the physical environment within which the person and the technology will need to operate (Hersh & Johnson, 2008a).

The HAAT model views assistive technologies as "extrinsic enablers", since they provide the means through which human performance is improved in the presence of disability (Cook et al., 2014). The functions that can be allocated to these extrinsic enablers will vary with their design. A powered wheelchair for example can be allocated few functions linked to movement and postural support. However, an access device such as an eye-gaze technology system is extremely flexible in the number and range of functions it can be allocated. As discussed in the Introduction, this flexibility can potentially lead to confusion between the activity and the assistive technology, with clinicians needing to play a role in ensuring these components are kept distinct. The HAAT model encourages the consideration of the Activity (a game, some communication software, a literacy exercise) and the Assistive Technology (the eye-gaze system) as separate but inter-related components but would steer stakeholders away from viewing the eye-gaze system as an activity in itself.

Of further relevance to this thesis is the implications of the HAAT model for teaching eye-gaze, particularly when that teaching involves the use of eye-gaze software training packages. There exists a risk that the software may provide too much support, leading to confusion about the skills which are being demonstrated. In designing such software, a balancing act needs to take place between teaching the principles of using the technology and ensuring that independence and agency is not taken away from the child. There is the potential for functions to be misallocated: with software seeming or claiming to demonstrate skills that may in fact be "scaffolded" by the design of the activity. To provide a concrete example, the use of a very short dwell time (the time for which a user must hold their gaze steady on an item in order to select it) and a very limited choice of one or two large items on the screen may provide the impression that a child is making meaningful choices. In fact, the software is providing such a high level of support that it becomes almost impossible not to make a selection if the child's eyes are oriented towards the screen. This presents a challenge for those working to select assistive technology solutions, in determining what level of support is required to make access easier, whilst ensuring that this does not take away purposeful intent from the child. This situation is further complicated, as will be discussed in Chapter 4, by the fact that many such software packages keep hidden the algorithms that they use to grade performance on an activity.

The HAAT model also provides a framework for describing the components of an Assistive Technology that has been widely used when modelling access systems (Fager, Bardach,

Russell, & Higginbotham, 2012; Griffiths & Addison, 2017; Higginbotham, Shane, Russell, & Caves, 2007). This will be discussed further in Section 2.5 below.

2.3.2 Matching Person and Technology (MPT)

The Matching Person and Technology (MPT, Figure 4) model is a theoretical model and series of assessment tools designed to place the individual at the centre of decision-making on assistive technology (Scherer, 1998). It has been described by its author as a framework for organising the influences impacting technology use (Scherer, 2004; Scherer & Craddock, 2002). The model is based on the established assessment principles of "feature matching", where a team will take account of the skills and preferences of the user, consider their environment and goals, identify the specific features of assistive technology products that are required and then select a device or system that best matches these requirements in the context of the user's abilities (Gosnell et al., 2011; Light & McNaughton, 2013; Scherer, 2004, 2005). The model is designed to complement the ICF, with the assessment process that accompanies it broadly following the ICF domains (Scherer & Craddock, 2002). As such, the MPT conceptualises successful use of assistive technology as a product of considering the needs of the person, their environment and the features of the technology.

The MPT brings together a person-centred approach and a technological focus (Craddock, 2006), with the needs and abilities of the individual mapped against specific features of the technology before, during and after input from an assistive technology service. The focus on change and re-evaluation over time means that the process of providing technology is not one of "snap shot" decision-making followed by discharge, framing the provision of technology as part of a longer process, rather than as the outcome of an assessment (Chantry & Dunford, 2010).

The MPT provides a framework for modelling not only the performance of the person and the assistive technology, but also the performance of the assessment and supply services involved in selection and provision. With the user considered the centre of this model, the MPT includes outcome measurements that are based on user satisfaction and enhanced quality of life (Hersh & Johnson, 2008a; Scherer, 2004; Scherer & Craddock, 2002).

The MPT seeks to recognise that the selection of a piece of assistive technology is not a simple case of matching a person's physical skills to features of a piece of technology. It has

been suggested that even the "best match" between person and technology can fail and result in abandonment if the person's goals, attitude and support structures are not taken into account (Craddock, 2006; Karlsson, Johnston, & Barker, 2017; McDonald et al., 2008). Therefore, assessments using the MPT begin with a review of the characteristics and preferences of the user, with clinicians encouraged to consider not only the physical skills or impairments of the individual, but also other personal, emotional and attitudinal factors of the user and their support network. In practice, this might include ensuring that the clinician understands the person's history of technology use, the confidence of the user and those around them with new technology and the attitude towards making use of technology to support achievement of goals.

Figure 4 - The Matching Person and Technology (MPT) model
(Scherer, 1998)

The model promotes consideration of the environment in which the individual functions. This includes not only the immediate physical environment, but also aspects of an individual's cultural and attitudinal environment which may impact on use of technology. Economic, legislative and political factors are also considered to acknowledge that the broader societal context may be a barrier or facilitator to the acquisition and support of technology. To reflect this broader consideration of the environment, this part of the model is also titled the "milieu" (Scherer, 2004).

The final component of the model focuses on the features of the technology, including its performance, appearance, cost, availability and comfort. The model encourages the prescribing clinician to view all three groups of factors (personal, environmental, technological) as inter-related. For example, a person with a negative attitude towards technology which makes them stand out or look different may compromise on some features of a system in order to make use of technology based on mainstream equipment.

Critics of the MPT have cited its complexity in everyday practice (Bernd, Van Der Pijl, & De Witte, 2009), its lack of flexibility beyond the published assessment framework and the reduced utility of its assessment component for users with severe and multiple disabilities; owing to its reliance on the user expressing preferences and being able to evaluate the technology (Hoppestad, 2007; Mumford, Lam, Wright, & Chau, 2014). Outside of the assessment tools, however, its focus on the skills and characteristics of the user means that the MPT model provides a solid conceptual foundation for ensuring clinicians have, as a starting point for any assistive technology or access assessment, a full understanding of the client's profile of strengths and difficulties. In the context of this study, the MPT provides a rationale for investigating the impact of impairments of vision and cognition on eye-gaze technology. Where the key feature of a technology is its control using the eyes, a robust understanding of how the individual uses their vision is warranted. In a similar way to the HAAT model, the MPT model helps position assistive technology as a "tool" to be used to accomplish goals, rather than its provision being an endpoint in itself. This has important clinical implications for managing the expectations of users, professionals and families.

2.4 Defining Access and Access Methods

In its simplest terms, access can be thought of as the physical interaction between a person and a computer: "the means by which an individual interfaces with the assistive technology" (Cook & Hussey, 1995). As new methods of controlling technology have appeared and as frameworks such as the MPT and the HAAT model have become widely used in clinical practice, it is acknowledged that any contemporary definition of access must look beyond the physical and technological aspects of how a user controls a computer, and take account of the activity, its context, the level of support from others and the demands of the task for which the computer is being used (Fager et al., 2012; Griffiths & Addison, 2017; Smith, 2019). This broader focus prompted Higginbotham and colleagues to offer the following contemporary definition of access in a paper focused on access to high-tech AAC systems:

"…[the] complicated interrelationship between the features of the AAC technology, the individual's physical (motor, sensory, perceptual) ability, cognitive / linguistic skills, and device users' and their communication partners' abilities to interact and communicate."

(Higginbotham et al., 2007)

The authors of this paper point out that a more nuanced, all-encompassing definition such as this one allows access to be considered in its broadest sense – as a system in which each of the components can be changed or adapted to meet the needs of an individual. Returning to the HAAT model's definition of assistive technology as an extrinsic enabler, the authors of this model propose that both general and assistive technologies have several common components which dictate how they interact with the Human and Activity components of the model. These components (visualised in Figure 5) represent the flow of information and forces through the Assistive Technology system and between this and the other components of the HAAT model (Cook et al., 2014).
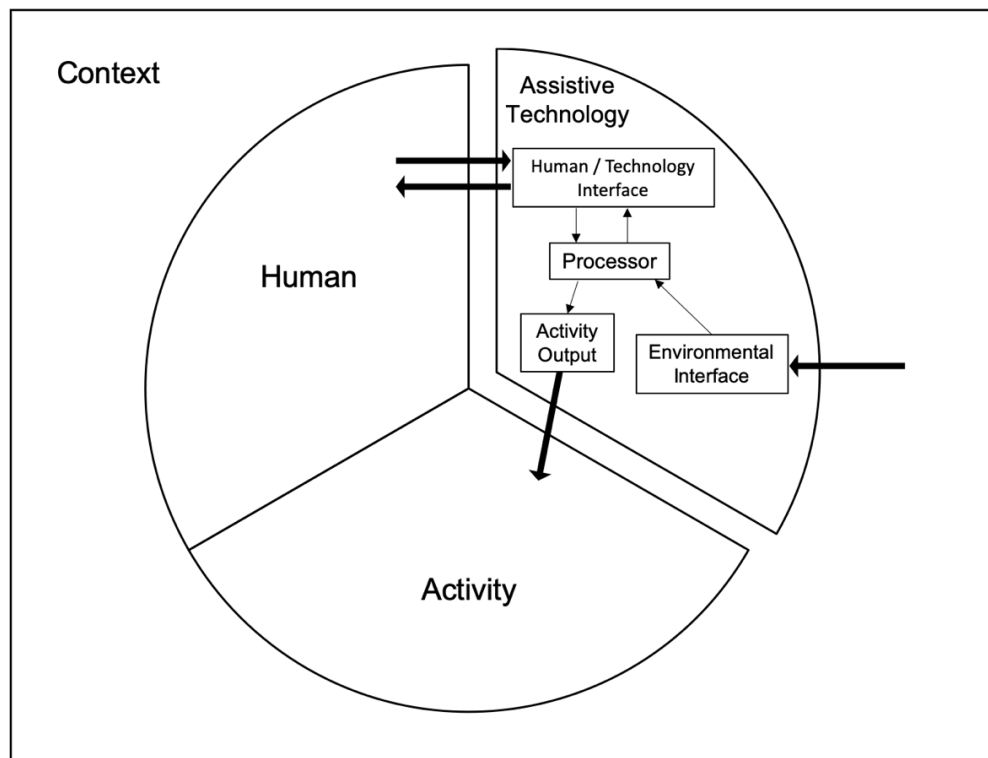
Figure 5 - Components of Assistive Technologies and their interactions with the Human and Activity components, as represented in the HAAT model (Cook et al., 2014)

The definition of access proposed by Higginbotham and colleagues is consistent with the conceptualisations of assistive technology set out by the HAAT model and the processes outlined in the MPT model: access is an interaction between person, task, assistive technology and context. It also considers the skills of those supporting the person with disabilities as part of their access system. Conceptualising access in this way has advantages for both clinicians and researchers. For clinicians, it allows the access system to be broken down into components that can be altered and adjusted to meet the user's needs (discussed further in Section 2.5 below). For researchers, the system being broken down in this way offers the opportunity to study individual components and interactions while controlling others.

In this model, the Human / Technology Interface represents the boundary between user and technology. It is this component which is the means by which the user controls the assistive technology. In the fields of AAC and computer access, this is referred to as an "access method". An access method is any system or piece of equipment that will allow independent movement to be translated into control of a computer or an AAC system (Griffiths & Addison, 2017) and it is an examination of the interaction between this component – and more specifically eye-gaze control – and children with cerebral palsy (CP) that is the starting point for the experimental work described in this thesis. In AAC and computer access, the Processor component of the model is the computer, software or voice output communication aid (VOCA) itself, which translates the human input into the Activity Output – in this case, the transmission of a spoken message or the control of onscreen action in a game. The final component of this system, the Environmental Interface, is less relevant to AAC and computer access, since it is primarily used for assistive technologies which take in sensory information from the environment, such as hearing or vision aids (Cook & Hussey, 1995; Cook et al., 2014).

Of crucial importance to the discussion of eye-gaze technology is the nature of the interaction between the user and the Human / Technology Interface. In the HAAT model, this interaction is two-way, with the user providing input to the access method and the access method providing feedback to the user. A widely understood example of this might be the auditory "click" of a mouse button or the proprioceptive feedback provided by the "travel" of a keyboard key. It is this interaction that raises another key issue for this research: that

the feedback given to the user by eye-gaze technology is significantly reduced in comparison to other access methods.

In order to maintain focus on this interaction, the work carried out in this thesis seeks to tailor the design of the activities to remove elements such as the production of language or communication, reducing the task demand as much as possible to allow focus on the skills needed to make use of eye-gaze technology. To provide context to the work, the following sections discuss the clinical processes which inform the selection of an access method.

2.5 Access Assessment

Access methods can range from the traditional ways of interacting with a VOCA, computer or tablet (a keyboard and / or mouse, a touchscreen) to the use of less standard input devices such as eye-gaze control or mechanical switches. As has been previously discussed, the selection of an access method is a highly individualised process and providing an access method for a person with physical impairment can require input from a variety of professionals working as a multidisciplinary team (MDT). Whilst the professional makeup of the MDT may vary, professional groups including Speech and Language Therapists, Occupational Therapists, Clinical Scientists or other Healthcare Science professionals including Rehabilitation Engineers and Technicians often form the core team (Chantry & Dunford, 2010; Enderby, Judge, Creer, & John, 2013; Griffiths & Price, 2011). Input from Medical Consultants, Physiotherapists, Nurses, Psychologists and Education Professionals is also sometimes required, depending on the needs and goals of the individual (Australian Cerebral Palsy Register, 2018; Karlsson et al., 2017). Irrespective of the professional skill mix, the team should have sufficient expertise in Assistive Technology and computer access, as well as in the specific task for which the access method is being sought, such as providing access to a VOCA or AAC software (Bache & Derwent, 2008; Wallis, Bloch, & Clarke, 2017). As advocated by the MPT model, professionals involved should contribute their expertise to the options and preferences of the user and their family or support team, in order to build consensus on appropriate access methods for trial and provision (Scherer, 1998; Scherer & Craddock, 2002).

In a 2017 paper, Griffiths and Addison proposed a model of access assessment for children with CP that takes the principles of carefully considering the client's skills and abilities set out in the MPT as a starting point. Whilst acknowledging the importance of the client's

preferences and activities, the authors of this paper propose the use of the ICF as a framework for clinicians to make decisions about access methods (Griffiths & Addison, 2017). In common with other assessment frameworks (Mumford et al., 2014; Scherer et al., 2007), assessment begins at the level of body functions and structure, observing the barriers to access presented by a user's posture, gross and fine motor skills, before matching these with the features of available technologies to address the task. This process is described in more detail in the following sections.

2.5.1 Posture and Seating

Assessment of access for a person with a physical disability normally begins with consideration of the individual's position and of any postural support equipment such as specialist seating that they are using (Costigan & Light, 2010, 2011). Poor seating or positioning can compromise the motor control of children with movement disorders such as CP and has been shown to impact negatively on upper limb function, which in turn impacts on the accurate control of a computer (Higginbotham et al., 2007; Sahinoğlu, Coskun, & Bek, 2017). Poor positioning is also related to difficulties maintaining head control and increase in fatigue (Fager et al., 2012).

2.5.2 Identifying Points of Control

Assessment for an access method starts at the level of the ICF domain of Body Structure and Function – considering the physical skills, movement and limb control of the individual. Once a suitable seating position has been established, clinicians will proceed with careful observation and assessment of the individual's movements, with the goal of identifying one or more "points of control". This term refers to a part or parts of the body where an individual can execute independent, purposeful, accurate, graded and repeatable movements (Griffiths & Addison, 2017). Assessment of both gross and fine motor control should be made to inform the positioning of an input device, its size and the accuracy required to activate it (Cowan & Najafi, 2019, p. 93). Clinicians may look at the range of movement, the functioning of muscles and joints and any factors such as tremor that might impact on accuracy (Costigan & Newell, 2009). Consideration of fluidity and accuracy ensures that the most reliable, consistent and therefore effective movement is chosen, although clinicians must also be mindful of possible long-term impacts of repetitive movements, such as contractures or abnormal limb posture. Whilst there exists no evidence for a "hierarchy" of control points (Myrden et al., 2014), starting with options that are physically intuitive, direct and non-complex from a cognitive

perspective is recommended (Fager et al., 2012). The role of the clinical team is then to identify an access method which can be controlled using the identified point or points of control.

All access methods can be seen as having several common, inter-related elements: an input device, a selection method, an array of items from which to choose and a method of providing feedback to the user. To select a reliable and efficient access method, clinicians should consider all four elements, with adjustments made to each according to the specific needs of the person accessing the system. The following sections using the guiding principles of the MPT model to discuss how a personalised access method can be arrived at through consideration and adjustment of these four components.

2.5.3 Selecting an Input Device

Perhaps the most obvious and familiar element of an access system is the input device, which is a peripheral which provides control signals to an AAC device or computer (Griffiths & Addison, 2017). In this, the input device can be seen as the most obvious physical representation of the HAAT model's Human / Technology Interface, being the item through which the individual interfaces with the technology. Examples of such devices from mainstream technology would include a keyboard, mouse or touchscreen. In the field of assistive technology, a range of modified and adapted keyboards, pointing devices and touchscreens exist to meet the individual needs of users, alongside more specialist technologies such as switch interfaces and eye-gaze access technology, providing other alternatives for users and clinicians.

An input device can provide either discrete input (such as a key or switch press) or continuous input (such as the movement of a cursor controlled by a pointing device). An input device can generate any number of individual signals, ranging from one (such as a single switch) through a variety of whole numbers (such as the 4 directional buttons on a D-pad controller or the 104 keys on a standard keyboard), to the theoretically infinite number of signals available when moving a pointing device or pointing to a touchscreen. As the number of input signals increases, so too does the level of accuracy required to control the input device. Continuing with the above example, a single switch is an input device that is physically easier to control than a standard keyboard. Returning to the MPT framework, selection of an input device is determined primarily by the movement that a user can make reliably, repeatedly

and accurately. For example, a child who has one reliable access point using the movement of their head, but does not have enough accuracy with this to control a head mouse or head pointer with sufficient accuracy, may be a good candidate for the use of a head switch to access a computer or VOCA.

For children requiring switches, a wide range of options are available; including mechanical switches of varying activation pressures, electrical switches and proximity switches which require no physical contact to activate. Some switches are designed for specific access points, such as pneumatic ("sip- puff") switches which can be controlled by changes in intraoral pressure. Recent developments in switches using electromyography (EMG) have provided the possibility of "on body" switching requiring very little physical movement, where electrical activity in muscles can be turned into digital signals for control of a device.

2.5.4 Identifying a Selection Method

The decisions made about an input device are interdependent with the choice of a selection method. Within the fields of AAC and computer access, selection methods are described as being either "direct" or "indirect". In simple terms, a direct selection method is one where a user points directly to their choice, without the need to navigate through other items in the array. This is typically achieved by pointing to an item with a body part or pointing device - either on a screen or a physical array such as a keyboard - and selecting it using a press or tap, or by holding the cursor stationary for a pre-determined period. An indirect selection method is one where the user "scans" through the options in the array in a systematic way in order to reach a target item, which can then be chosen using the input device (Griffiths & Addison, 2017).

2.5.5 Direct and Indirect Selection

Where the physical skills exist to make use of them, it is generally recognised by professionals that direct selection methods are faster and more intuitive than indirect selection methods. Research in the field has indicated that an inverse relationship exists between the cognitive and physical demands of these two selection methods (Wagner & Jackson, 2006). Studies have shown that a one-to-one relationship between the control point and the item being selected is more transparent to children and is cognitively easier to master: requiring less planning (Petersen, Reichle, & Johnston, 2000), placing lower demands on working memory (Mizuko, Reichle, Ratcliff, & Esser, 1994; Ratcliff, 1994) and on concentration (Horn & Jones,

1996). The requirements for accurate control and reliable movement are much higher, however, and increase according to the number of items presented for selection (Nisbet, 2019)

Conversely, scanning imposes minimal motor demands on a user; potentially requiring only one single reliable movement to activate a switch (McCarthy et al., 2006), although setups with multiple switches are also a possibility. Scanning is however a slower method of access, with a recent systematic review revealing that even text users with no cognitive impairment produced an average of only 1.7 words per minute (WPM) using a scanning keyboard (Koester & Arthanat, 2018). This is roughly 100 times slower than conversational speech rate of 120 WPM and slower than the average output rates of direct access users of 2 - 14 WPM (Beukelman & Mirenda, 1998). In the same systematic review, the best reported text entry rate for a literate user using a scanning keyboard was 6.51 WPM, which was achieved using a highly customised array and a number of rate enhancement strategies such as word completion and word prediction (Koester & Arthanat, 2018; Koester & Simpson, 2014). Changes to the layout of the items on screen (Mankowski, Simpson, & Koester, 2013) and the use of word prediction and other "rate enhancement" techniques (Koester & Arthanat, 2018) can improve speeds, but it remains the case that indirect access via scanning is a slower method of making selections than direct access.

Indirect access also requires more advanced cognitive skills. Several studies have demonstrated that scanning is difficult for children to learn, with typical three and four year olds finding any type of scanning very difficult to master (McCarthy et al., 2006). One such study (Petersen et al., 2000) showed that almost half (11 out of 23, 48%) of typically developing children of pre-school age (M_{age} = 37 months, *Range* = 30 − 42 months) were unable to make use of either linear (where the cursor scans each item in turn) or row-column scanning (where the cursor highlights each row in turn until one is selected and then highlights each item within that row) to select even a single item from an array of 40 items. This performance was not affected by instruction and explicit modelling from the researchers, indicating that use of scanning as a selection method was not obvious or transparent for these children. It is not unreasonable to infer that the challenges facing children with severe physical impairment would be even greater. Several other studies (Dropik & Reichle, 2008; Marina, Drynan, & Tiessen, 2012) have produced similar findings. Indeed, a control group of typically developing two year-olds in the study by McCarthy and

colleagues (discussed in more detail below) were not able to show any improvement in accuracy of selection using linear scanning after three sessions totalling 30 – 60 minutes, suggesting that young children find the concept of indirect access challenging (McCarthy et al., 2006).

Where indirect selection methods are required, a variety of methods to increase speed of selection are available. For example, if the user can access an input device with four switches, directional scanning may be a possibility, allowing horizontal and vertical movement of the scanning highlight. Some studies have suggested this method of scanning, which is conceptually closer to use of a direct access method such as a joystick, may have some advantages for children able to access the required number of switches. One study (Dropik & Reichle, 2008) reported a significant increase in accuracy of selection with directed scanning when compared to group-item scanning (similar to row-column scanning described above), suggesting that children found this method less difficult.

McCarthy and colleagues proposed a model of scanning which has been redesigned to reduce learning demands (McCarthy et al., 2006). In their model, the items in the array appear animated (enlarging, moving forward) as they are scanned. This is accompanied by a "prompt" voice with rising intonation, simulating the posing of a question. These visual and auditory cues were intended to mirror the way in which choices are offered to children in play. Feedback on selection was also made much clearer, with the selected item being enlarged, moving to the centre of the screen and the auditory cue saying the name of the item. Typically developing two-year-olds were assigned to a group using either traditional (linear) scanning or the "enhanced" method of scanning described above, with both groups given three sessions of 10 – 20 minutes each with the scanning tasks. Results showed that the group using traditional scanning made no gains in accuracy across the three sessions (20% accuracy across nine trials in the first session, 14% in the second session and 20% in the third session), whilst significant gains were noted in the enhanced scanning group (22% accuracy across nine trials in the first session, 39% in the second session and 48% in the third session). Whilst these results are impressive, it is worth noting that these levels of accuracy are still below those which would be expected for direct access selection using a touchscreen (Cook et al., 2014). Additionally, the enhanced scanning technique described in this study has yet to be trialled in real-world settings or with children with disabilities.

For the reasons outlined above, direct access methods are generally preferred by clinicians where the physical skills of the child are sufficient for control (Beauchamp, Bourke-Taylor, & Brown, 2018; Fager et al., 2012; Griffiths & Addison, 2017). Although the use of switches and indirect access methods is encouraged for some client groups and should be considered as part of a full access assessment (Z. Clarke, Rouston, Wade, & Farrand, 2019; Rouston, 2019), direct access methods are often preferred in the first instance, since they are generally considered to be faster overall and easier to learn and teach. As will be discussed further in the coming chapters, eye-gaze technology may provide a challenge to this, since there are aspects of the technology that make instruction more challenging for professionals supporting new users.

2.5.6 User Feedback

In order for an access method to be useful, it must provide feedback to the user; indicating what options are available in the selection set, which items are being targeted for selection and alerting the user that they have made a successful selection (Griffiths & Addison, 2017). In many cases, a feedback system will comprise a visual array of items on a screen, with the mouse cursor or scanning highlight showing what is currently being targeted by the user and a "click" from the switch or mouse button indicating that a selection has been made. To use an example from clinical practice, a person who is able to manipulate a mouse cursor but not able to affect a click may make use of "dwell clicking", where the cursor is held on an item for a pre-defined period of time in order to select it. Feedback to the user in this example is provided by the mouse cursor, with the item being primed for selection highlighted when the cursor enters its activation area. A visual indicator of the dwell such as a clock marker or the item changing colour may be used, followed by an indicator such as a click to indicate that the selection has been completed. Feedback systems can be extensively customised to meet the individual needs of the user. For example, where a person has profound visual impairment, a feedback system which includes auditory-only cues may be considered. In addition, the tactile or haptic response from the click of a key, mouse button or switch can be augmented with a brief change in colour of the selected item to provide extra feedback.

2.5.7 Selection Set

The selection set is comprised of all the items which are presented to the user for selection (Beukelman & Mirenda, 2012; Griffiths & Addison, 2017). On a VOCA or communication software package the selection set might include letters, words, whole phrases or graphic

symbols, as well as navigational cells and functional commands (such as *speak*, *clear display* etc.). For computer access, the selection set may include elements of the operating system and items which simplify complex processes by sending strings of commands to other pieces of software. In mainstream technology, a good example of a selection set is the keyboard, where the user needs to select the correct letters from the array in order to input words or commands. The selection set differs from the selection method in that the array of items can be almost endlessly varied, while the method used to select those items remains constant.

The layout and presentation of items can play a key role in ensuring that an access method allows the user to make choices quickly and efficiently, with minimum effort and fatigue (Light & Drager, 2002). For example, where a user is accessing a VOCA via indirect selection with switch scanning, it will be important to place frequently used items high up in the scanning order, so that they may be selected in a shorter amount of time and with fewer switch presses (Beukelman & Mirenda, 2012).

2.5.8 Challenges for Clinicians in Access Method Selection

The above sections have demonstrated the wealth of options available to clinicians when designing an access method for a client. Evidence for the use of specific access methods with particular client groups is sparse, with the small numbers involved in studies often making results difficult to generalise. A recent summary article looked at access methods for children with CP and reported that the evidence on which clinicians may draw when making decisions "is not yet robust and is largely based on case study or case series reports" (Myrden et al., 2014, p. 1114). The authors of this review conclude that, as the number of access methods available to users and clinicians grows, the role of assessment becomes ever more important.

In recent years, the advent of eye-gaze technology has provided a challenge to the established paradigm that direct access methods are faster to learn, more intuitive and provide greater levels of user feedback. Whilst it is a direct access method and, in its simplest form, is essentially a pointing device; the one-to-one relationship between control point, input device and selection set is not as transparent as it is with a touchscreen, stylus or even a mouse and keyboard where the input method is displaced from the other components of the system. In addition, the user is provided with no proprioceptive feedback when making movements or selections, and several authors (Higginbotham et al., 2007; Tai, Blain, & Chau, 2008) have observed that there is no means of distinguishing between the input method and

other user activity (visually exploring the choices available on the screen). Such systems are therefore more prone to errors caused by the device's misinterpreting exploration of the screen for purposeful input. This is explored in more detail in Chapter 5, where it is proposed as one of the key challenges for researchers and clinicians working with this technology. Questions around the different types of feedback provided by eye-gaze technology and the potential challenges of inferring a causal relationship between eye movement and control of a device are addressed further in Chapter 8 of this thesis, where performance on an eye-gaze control task is compared with performance on the same task using a touchscreen.

2.6 Structure and Function of the Human Eye

In order to fully describe the process by which an eye tracker or eye-gaze control device estimates the direction of a user's gaze, it is first necessary to briefly discuss the structure of the human eye, how it operates and how it generates images. The key components of the human eye are shown in schematic form in Figure 6.

The adult human eye is approximately spherical, with a diameter of approximately 24mm (Bekerman, Gottlieb, & Vaiman, 2014). The outer wall of the eye, which is known as the sclera and often referred to as the "white of the eye", is composed of several layers, with an outer layer of collagen keeping the eye's semi-rigid shape. The sclera covers five-sixths of the eye's external surface, with the exception being the area at the front of the eye where it joins the cornea at the limbus (Van Buskirk, 1989). The cornea is a transparent layer which allows light to be admitted to the interior of the eye.

Light, reflected from objects in the environment, enters through this aperture at the front of the eye and is refracted to focus on the light-sensitive cells covering the retina at the rear. When light enters, it first passes through the cornea, which serves the dual purpose of acting as a protective layer for the more delicate optical elements of the eye and acting as a lens with a fixed refractive power (Navarro, 2009). Behind the cornea, light then passes through the aqueous humor, a transparent reservoir of liquid, the pressure of which maintains the curve of the cornea. Next, light passes through the pupil: a circular aperture the dimensions of which are defined by a ring of muscle called the iris. Pupil size is determined by the contraction or dilation of the iris in response to light levels, with the iris constricting to shrink the pupil as light levels increase and relaxing as light levels decrease. The average pupil size

in adults is between 2 and 4 mm in bright light and between 4 and 8mm in the dark (Spector, 1990). In healthy subjects, pupil size is typically equal in both eyes.
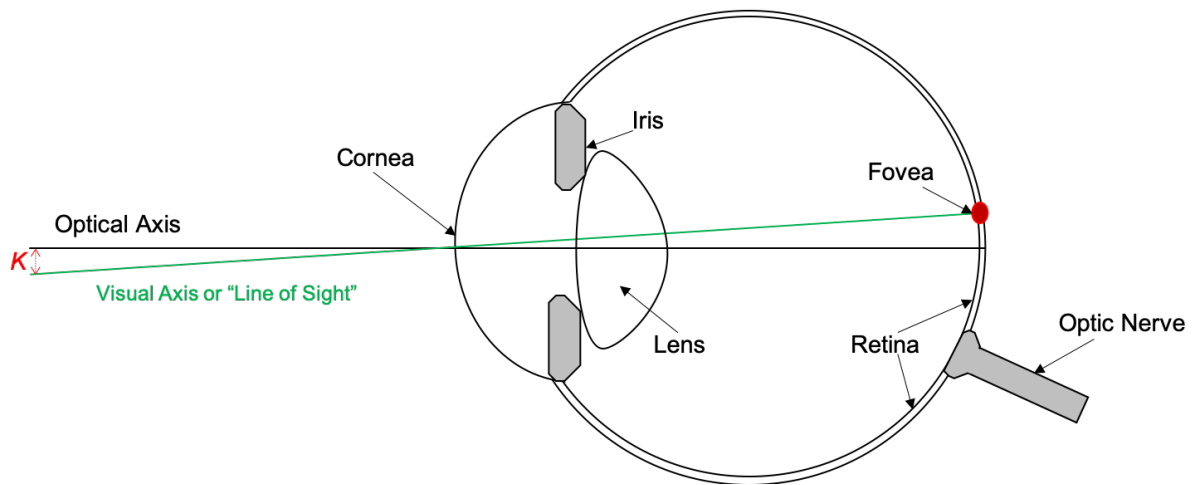
Figure 6 - Vertical cross-section schematic diagram of the structure of the human eye, showing both optical and visual axes (not to scale).

Light then passes through the lens, which focuses the image onto the retina at the rear of the eye. The shape of the lens is controlled by the ciliary muscle, which is a ring of muscle that makes the lens either more spherical for near vision, or flatter for distance vision. Typically, the refractive power of the cornea equips the eye well for distance vision and it is the refraction provided by the lens that allows for focus on nearby objects. This process is known as accommodation.

Between the lens and the retina, the interior of the eye is filled with a transparent, gel-like liquid called the vitreous humor. Although made up mostly of water, the vitreous humor has a viscosity of 2 – 4 times that of water and it is the pressure of the vitreous humor against the inner layers of the sclera that keeps the eye in its spherical shape (To, Kong, Chan, Shahidullah, & Do, 2002). The vitreous humor also aids with the refraction of light onto the retina and, due to its transparency and low concentration of particulates, ensures that light does not "scatter" within the interior of the eye (Navarro, 2009).

The retina itself is made up of light-sensitive cells called photoreceptors, which turn light into electrical signals which are then transmitted to the brain via the optic nerve. In this respect, the retina is often compared to photographic film in a camera. The photoreceptor cells are divided into two categories: rods and cones. Rods are specialised to detect contrast, movement and brightness, whereas cones are sensitive to colour and fine resolution or detail

(Purves et al., 2001). The distribution of rods and cones varies across the retina, with rods predominating for the majority of the surface area, particularly towards the periphery of the retina where cones are almost entirely absent. Central to the vision of all primates is a small area of the retina called the fovea centralis, most commonly referred to simply as the fovea, which is an indentation at the centre of the macula region (the word "fovea" derives from a Latin word meaning "pit"), where the cones are most densely packed together with almost no rod cells present (Hendrickson, 2009). The fovea is an extremely small area of the retina, measuring only 0.35mm in diameter. As a result, the fovea is the area of the retina most effective at processing visual information, and it is the only area at which maximum visual acuity or "20/20 vision" is achievable. The fovea can therefore be thought of as the central point of human visual attention and, since it accounts for only around 1° of a person's total visual field, the eye continually adjusts its angle and position (using small movements known as saccades) to keep the object of focus available to the fovea (Karatekin, 2007). A commonly used example of this is reading text: in this process, the eye is continually adjusted to "foveate" on each word. When the word is centrally located and the light reflected from it falls onto the fovea, the word is able to be read. Within the brain, foveal vision is prioritised to such an extent that studies have demonstrated that around 25% of the visual cortex is dedicated to the processing the 2.5° of the visual scene falling within the foveal and parafoveal areas of the retina (De Valois & De Valois, 1980).

Crucially to the estimation of gaze by an eye tracker or eye-gaze control system, the fovea is not centrally positioned on the optical axis of the eye (the theoretical line that passes through the centres of curvature of the cornea and lens, and meets the retina at its geometric centre (Srinivasan, 2016), see Figure 6), but is rather located approximately 4mm temporal and 0.8mm inferior to the centre of the optic disc (Hendrickson, 2009). The line joining the centre of the fovea and the centre of the cornea is called the visual axis, or "line of sight", and it is this line which an eye tracker uses to define gaze position. The visual axis is offset from the optical axis by approximately 5°. In eye-tracking literature, this angle is often termed kappa (*K*). This offset will be different for each person and determining the angle of offset is the goal of calibrating an eye tracker or eye-gaze control system. This process is discussed in more detail below.

The human eye's basic biological function is to take in information about the environment or a particular object of interest and relay this to the brain for processing and action. To

facilitate this, the eye is moved by six external muscles, which allow it to scan the environment or fixate steadily on a particular point. These muscles are arranged in three pairs, allowing precise control of horizontal, vertical and torsional movement (K. Holmqvist et al., 2011). Where a larger adjustment of the visual field is required to take in information, a person may also move their head and neck to keep an object in range. As is discussed further in the next chapter, the relationship between head and eye movements develops early in life (Daniel & Lee, 1990) and is considered to be linked to unconscious predictions of how long a fixation will last. If the likelihood is that prolonged fixation will be required, the eyes and head move together to locate a peripheral stimulus within the fovea, whereas if this is not likely to be the case, the eyes will orient independently for a brief duration (Oommen, Smith, & Stahl, 2004).

What the above introduction seeks to make clear is that the human eye has evolved to foveate the object of interest at any given moment: to make more available to the brain the object or item that needs to be visually processed. As a result, the main function of an eye-gaze or eye tracking computer can be thought of as determining what is being foveated at any given time. The following sections explain how this is achieved through a process known as "gaze estimation".

2.7 Eye-Gaze and Eye Tracking Technology

This section outlines the basic components and setup of both eye-gaze and eye tracking technology, as well as summarising the differences between the two terms and the technologies they describe. The chapter concludes with a description of how these technologies estimate gaze position and direction.

At the time of writing, interest in and use of eye-gaze and eye-tracking technology is growing rapidly, with the global market valued at $285.6 million in 2017. In this same year, it was estimated that the healthcare sector accounted for just over 24% of revenue share, with principal applications being the use of the technology to provide "a computer interface for patients suffering from mobility disabilities and other communication issues" (Grand View Research, 2018). The recent growth in the sector and increased interest and awareness from people using AAC and their families has led to a wealth of new hardware and software being brought to market by established AAC suppliers and new assistive technology companies. This section therefore aims to provide some background information on the technology. It

should be noted at the outset that, whilst manufacturers offer systems that may differ in performance and capability, it is beyond the scope of this thesis to enter into comparative discussion of their relative merits, nor is it the author's intention to endorse any particular device or software. What follows is therefore a general discussion of the technology, without dwelling on the specifics of one particular system or manufacturer.

2.7.1 Terminology

It is often the case that "eye-gaze" and "eye tracking" are used interchangeably, with several assistive technology suppliers using them as synonyms to refer to the technology that allows active control of a computer or VOCA. Researchers (see Wilkinson & Mitchell, 2014, for example) have found it helpful to draw a distinction between the terms and the use of both technologies in the chapters that follow means discussion of the distinctions between them is warranted at the outset.

The distinction proposed is that "eye tracking" or an "eye tracker" refers to a technology that passively captures and records data from a user's eye movements. In an eye tracking paradigm, the user does not need to do anything: the eye tracker automatically captures their reflexive and volitional eye movements in response to onscreen or environmental stimuli.

Gathering data through eye tracking is a process that has found application in a range of fields including psychology, sports science, advertising and human-computer interaction (Karatekin, 2007). The use of gaze to provide information on what is being made available to the brain has been well established for more than one hundred and fifty years. In 1879, the ophthalmologist Louis Èmile Javal used direct observation to reveal that the eyes did not "sweep" over written text, as had been previously assumed, but rather they moved in a series of "jumps". It was Javal who coined the term "saccade", meaning "jerk", for these movements. Continuing along these lines, Edmund Burke Huey conducted the first study using a more formal eye tracking method in 1908, entitled *The Psychology and Pedagogy of Reading* (Huey, 1908). This study made use of the first mechanical eye tracker, where a "cap" was placed over the over the front of the eye, which was linked to a pen that traced the movements of gaze onto a rotating drum, which could then be overlaid on the original text to reveal the path of the users' gaze (Wade, 2010). In the 1920s, as camera and film technology advanced, Judd and Buswell developed the first non-invasive gaze tracking

paradigms using cameras to closely observe the movement of a users' gaze and record them for analysis after the experiment (Wade, 2010). In the 1950s and 60s, the psychologist Alfred Yarbus made extensive use of camera-based trackers to publish several important papers, demonstrating the relationship between eye fixations and attention and examining how the eyes are used to solve problems when provided with a stimulus (Tatler, Wade, Kwan, Findlay, & Velichkovsky, 2010; Yarbus, 1967). This work was continued by Just and Carpenter into the 1980s to demonstrate the "eye-mind hypothesis", which demonstrates the link between gaze and attention, stating that the eyes fixate on what the mind is processing (Just & Carpenter, 1980; Schindler & Lilienthal, 2019).

Modern eye trackers which use remote tracking techniques (see Section 2.7.2) can be classified as being either "static" or "desktop" systems (which are attached to a fixed point with the user seated in front of them) and "head mounted" or "environmental" systems (attached to the user, typically by being mounted on the frame of a pair of glasses). They can record the user's responses to items on a screen or other flat surface and can, with the addition of a "scene camera" (a camera that records what is in front of the subject) be used to record responses to the wider environment, with software being able to overlay the gaze data onto the scene camera retrospectively to gain insight into where a person looked during the experiment. Head mounted and environmental trackers are not used for the procedures described in this thesis due to their reduced utility for people with disabilities (Kar & Corcoran, 2017) and the remainder of this chapter deals only with static or desktop trackers. In addition, this thesis focuses only on non-invasive methods of eye-tracking: those using remote tracking based on using reflection. Whilst other methods do exist, such as the use of specially adapted contact lenses or electrodes placed on the skin near the eyes, these are not commonly used in assistive technology or disability studies as they tend to be more uncomfortable and invasive for the user.

An eye tracker can capture information on a range of eye movements, including both temporal and spatial data. These include the location of a user's gaze point, timing and velocity of saccades, duration of fixation, distance from the screen and pupillary dilation. For a comprehensive overview of the data which can be captured by an eye tracker, the reader is directed to the early chapters of *Eye Tracking: A Comprehensive Guide to Methods and Measures* (K. Holmqvist et al., 2011). The systems are used for data collection and analysis but, crucially, do not provide the user with any control of the device to which they are

connected. Typically, an eye tracking system will sample the user's eyes at a faster rate than an eye-gaze control system (at perhaps 60 – 120 Hz, meaning gaze point data is captured every 8 – 16 ms), thus requiring more processing power to handle the large amounts of data generated in reporting even the tiniest eye movements.

By contrast, the terms "eye-gaze", "eye-gaze control" or "eye-gaze technology" refer to the combination of a camera to track a user's eye movements and specific software processes which convert raw gaze data into a method to control a computer or VOCA. In this sense, eye-gaze devices act as the Human / Technology Interface described in the HAAT model and, when paired with a computer or VOCA system, encompass all four components of an access method as described in Section 2.5: providing an input method (the eye-gaze camera itself), a selection method (dwell, blink, an additional switch), a selection set (the array of symbols or letters on an AAC system, the icons and windows of an operating system, or the target items in a game) and user feedback (the action resulting from the selection of an onscreen item).

Eye-gaze technology can facilitate access to the operating system and other software environments either through direct control of the mouse cursor or with the support of specifically written software. This may include AAC software or specialist "computer control" software which maps functions such as launching programmes or running sequences of commands to single, easily accessible buttons or cells onscreen. Since the demands for precision measurement and recording of data are not present in these systems, they tend to sample gaze data at a lower rate – around 30 Hz or one gaze point sample every 32 ms. This sampling rate is sufficient to allow smooth, continuous control of an onscreen cursor, whilst not imposing prohibitive needs for extra processing power and battery life.

In functional terms, the key difference between an eye-gaze control system and an eye tracker is whether the user interface is active or passive: whether gaze is being tracked for use as an input modality or whether eye gaze data is collected to understand user interest or attention (Kar & Corcoran, 2017). Both eye trackers and eye-gaze control systems use similar hardware setups, but the delineation proposed here is based on what is done with the gaze point data once it is acquired. Referring back to the HAAT model (Figure 5, Page 49), the difference between the two types of system can be characterised by whether data is passed to a Processor for use in Activity Output, or for logging and analysis. As such, an eye-

gaze system is an assistive technology device, whereas an eye tracker is not, since it performs no enabling function.

2.7.2 Basic Methods Used in Gaze Estimation

As discussed above, the hardware setup for eye-gaze and eye tracking technology are essentially very similar. Both systems use periodic sampling of the position of the participant's eyes to determine gaze position, with samples taken at rapid intervals. Most modern eye trackers use a process called "pupil-corneal reflection" (or simply "corneal reflection") to determine the position of the eyes and ascertain the focal point of the user's gaze. This process uses several components common to all modern eye trackers: a camera and image processor, one or more infra-red projectors and a display to provide the stimulus or selection set and to give user feedback.

In corneal reflection, the position of the eyes at each sampling point is determined on the basis of light reflected from the curvature of the cornea and the position of one or both pupils (Wilkinson & Mitchell, 2014). To accomplish this, eye-gaze and eye tracking systems make use of one or more infra-red emitters, which are positioned near to the camera and which project a low level of infra-red light towards the user. Infra-red light is used to avoid natural light interference when tracking and recording.

As the infra-red light falls on the cornea, some of it is reflected directly back towards the light source and some is reflected back at an angle determined by the curve of the cornea and lens. These reflections are known as the Purkinje Images (Figure 7) and occur at the boundaries between: air–cornea (P1), cornea–aqueous (P2), aqueous–lens (P3), and lens–vitreous (P4) (Srinivasan, 2016). It is the reflection P1 from the surface of the cornea that is particularly important to gaze estimation, since it is typically the brightest, and it is this reflection, commonly referred to as the "glint" (Hansen & Ji, 2010) that is used by most commercially available trackers and almost all eye-gaze devices. Whilst eye tracking systems exist that make use of two or more reflections, these tend to have more specialist applications such as using the difference between P1 and P4 to measure accommodation and therefore track the user's observations of a 3D environment (Morimoto & Mimica, 2005).
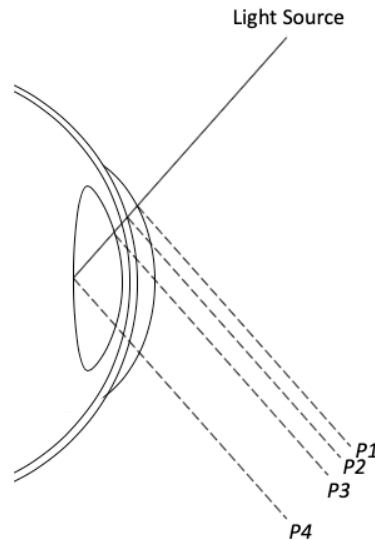
Figure 7 - Diagram showing the four Purkinje Images, the first of which is often referred to as the "glint" (not to scale)

The camera is therefore able to observe the glint as a bright spot on the surface of the eye. The glint serves two functions in eye tracking. Firstly, as it is likely to be the brightest part of the image acquired by the camera it helps to direct the image processor towards the part of the image in which the eye is located. This is particularly important when the user has a lot of head movement and improves the performance of a system by requiring less processing power to identify the position of the eye within the image captured by the camera. A commonly reported problem with eye-gaze systems is the acquisition by the image processor of a "false glint", which may be caused by the reflection from the lenses or frames of a users' glasses or similarly reflective objects in range of the camera. This can confuse the tracking algorithm and clinicians are recommended to attempt to minimise false glints wherever possible. Secondly, the glint plays a role in gaze estimation, as described below. For accurate gaze estimation to take place, however, the camera must also identify another feature of the eye, the pupil, which appears as a circle surrounded by a contrasting ring (the iris).

In the image acquired by the camera, the pupil can appear either as a dark or a light circle: referred to as "dark pupil" (Figure 8) or "bright pupil" (Figure 9) tracking. The different types of image that are produced depend on the position of the infra-red emitters, relative to the camera. Where the emitters are positioned coaxial (or near-coaxial) with the camera, the pupil is rendered as a light circle within a darker ring (the iris). This effect is caused by the infra-red light being reflected back from the retina. Where the emitters are offset from the

camera, the pupil appears as a dark circle within a lighter ring. In either case, it is the difference in contrast between the two circles, and the threshold where the two circles meet, that the system uses to determine the location of the pupil.
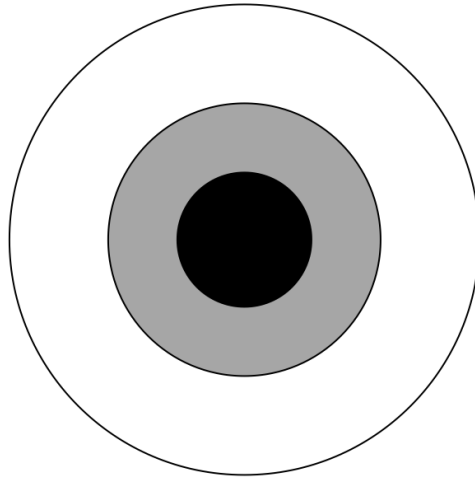
Figure 8 - Graphical representation of dark pupil tracking, where the pupil appears as a dark circle with a lighter contrasting ring.
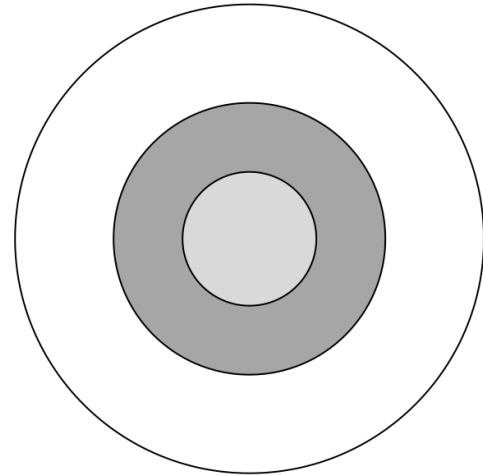
Figure 9 - Graphical representation of bright pupil tracking, where the pupil appears as a light circle with a darker contrasting ring.

Dark pupil tracking is currently by far the more common due to its relative technological simplicity and better accommodation of head movement. Bright pupil tracking does have some advantages, despite the design and engineering challenges of presenting the light source at the same axis as the camera. Since the technology was originally developed to compensate for poor contrast sensitivity in early eye tracking cameras (K. Holmqvist et al., 2011), bright pupil tracking can be useful for tracking the eyes of ethnic groups who have less colour differential between the iris and pupil, such as people of Afro-Caribbean heritage. The technology can also be better suited for people with no head movement such as users with locked-in syndrome or amyotrophic lateral sclerosis (Ball et al., 2010). Bright pupil tracking performs less well when the user has a lot of head movement, or when there is lots of ambient light which may result in pupil contraction. With improvements in contrast differentiation, dark pupil tracking has become the dominant technology, being the default choice for most eye-gaze control devices used in AAC and alternative access and meeting the needs of the majority of users. However, some eye tracking systems (such as the *Tobii T Series* devices) make use of two sets of emitters, dynamically switching between the two when acquiring an image of the eye.

Figure 10 - The image from an eye-gaze camera showing the eyes and glints
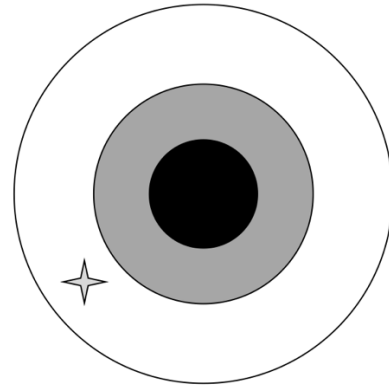
Figure 11 - A graphical representation of the image observed by an eye-gaze or eye tracking camera, showing the pupil, iris and glint.

Once the camera has acquired the image, the system then uses an image processor to analyse the camera data and calculate the centre point of the glint and of the pupil as shown in Figure 12. The glint and pupil centres are identified by the image processor using algorithms, which typically look for pre-determined patterns or parts of the image that match a pre-programmed "model" (Hansen & Ji, 2010). For example, the image processor may be "trained" to identify the brightest point in the image, which may be reasonably assumed to be the glint as this is where the highest density of infra-red light will be concentrated. Similarly, the system will look to identify a round, black circle within a brighter contrasting ring as the pupil. Holmqvist and colleagues observe that the methods and algorithms by which an image processor identifies these two features can vary enormously from manufacturer to manufacturer, and even between cameras made by the same company (K. Holmqvist et al., 2011). A further complication for researchers is presented by the fact that manufacturers will also keep some of these key technical differences confidential, classing them as commercially sensitive information. This can make comparing the performance and accuracy of different trackers difficult for the user community.
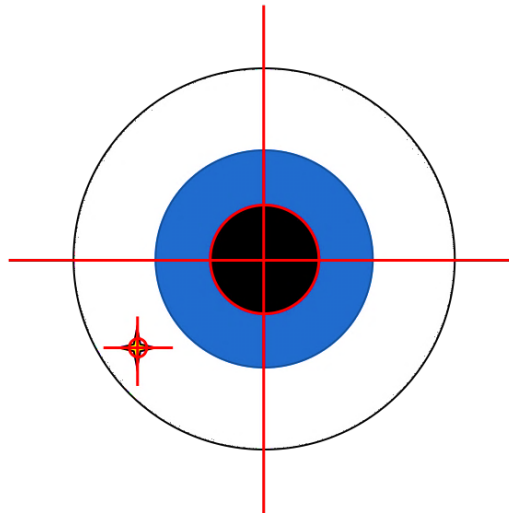
Figure 12 - Representation of the pupil and glint, overlaid with crosshairs showing the centre of each
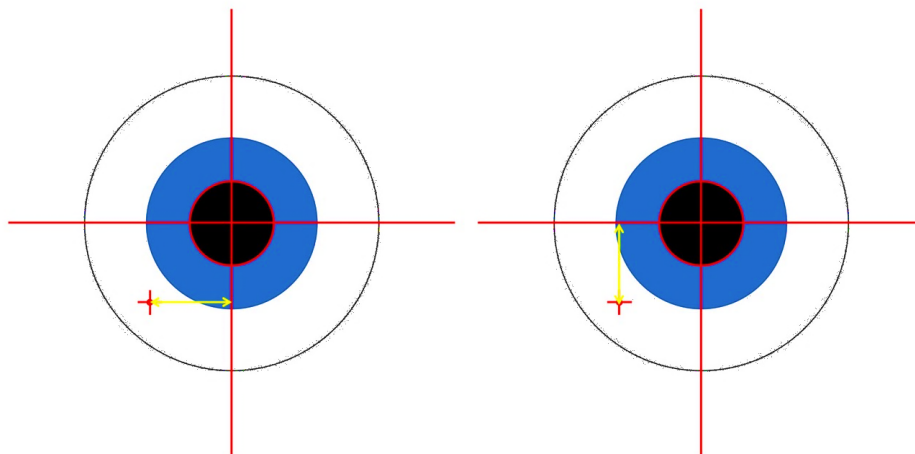
Figure 13 - Graphical representation of the offset between pupil and glint centres on both the x axis (left) and y axis (right)

The need to determine the centre of both the pupil and the glint arises from the fact, discussed above, that the line of sight does not run directly along the optical axis. Having identified the central points of both the glint and pupil, the system is then able to use the distance and offset between them (Figure 13), to determine the orientation of the eye. In a hypothetical setup where the camera and emitters are in a fixed location and the eye is exactly spherical and rotates only around its centre, the glint would stay at a single location on the surface of the cornea and the centre of the pupil would move, changing the vector between them. This can be used to identify the optical axis using a set of assumptions about

the dimensions of the eye and the laws that govern the reflection of light (Guestrin & Eizenman, 2006; Morimoto & Mimica, 2005).

At this point, a calibration procedure will allow the device to observe the position of the pupil centre and glint when the user is fixating on various known x-y co-ordinates on the screen. This allows calculation of the Kappa offset (*K*) and therefore the line of sight (E. Holmqvist, Thunberg, & Peny Dahlstrand, 2017; K. Holmqvist et al., 2011). Data on how far the user is from the screen is also used to determine the location at which the line of sight intersects with the display, meaning that the true location of the users' gaze can be identified. This location is often called the "point of gaze" or "gaze point". For binocular tracking, the values from the left and right eye are averaged to provide one single gaze point.
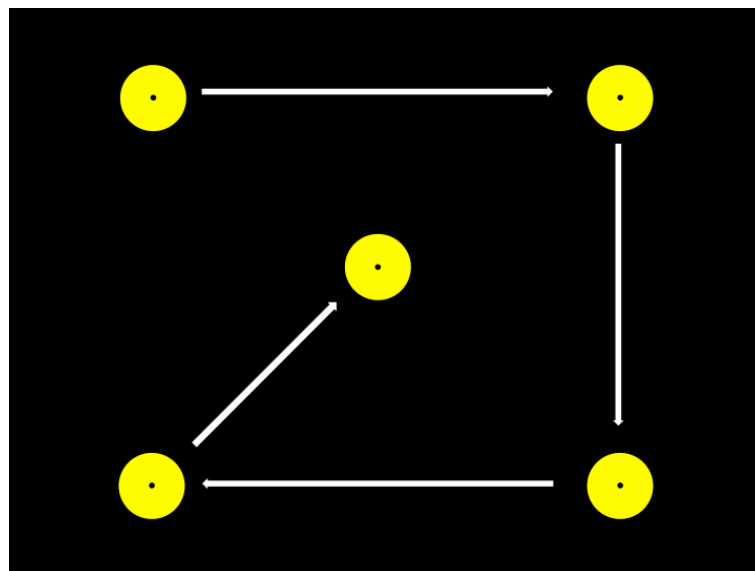
Figure 14 - Graphical representation of a five-point calibration procedure with arrows showing the direction in which the stimulus moves, stopping at each location to allow the eye tracker to sample the position of the users' eyes.

2.7.3 Calibration

Calibrating an eye tracker is an important part of both clinical intervention and data gathering for research. In essence, calibration is necessary because every user's eyes are subtly different in shape and size, meaning that the models available to the eye tracker or eye-gaze control system can never be entirely accurate and need adjusting for each user. A calibration is needed to calculate the changing vector between the glint and the pupil centre for each individual in order to accurately determine the line of sight (Dalrymple, Manner, Harmelink, Teska, & Elison, 2018). Calibration ensures that data gathered from an eye tracker

is valid or that a child has accurate control over the access method if using an eye-gaze device. It is frequently observed in the literature that data generated from an eye tracking study is only ever as good as the calibration (Feng, 2011; Oakes, 2012). Without accurate calibration, data collected by an eye tracker would likely be considered invalid, especially if small stimuli are being used. For an eye-gaze system, a good calibration can substantially increase accuracy and therefore performance, potentially allowing more items to be included in the selection set.

A calibration procedure involves the user fixating on a number of points on the screen, the x-y coordinates of which are predetermined by the software (Figure 14), and which form a grid from which all subsequent gaze points are interpolated (Feng, 2011). Capturing information about the pupil and glint centres whilst the user looks at each of these points allows the system to calculate the line of sight as described above. In order for a user to record a calibration, thresholds of accuracy and precision must be met, where the recorded gaze points are either located spatially close together, dispersed evenly around the target location, or both (Figure 15). The information about the offset of these gaze points is then added to the tracking algorithm for more accurate tracking.
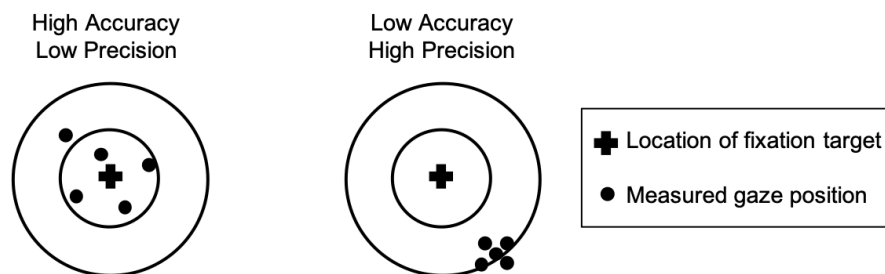
Figure 15 - Schematic diagram showing accuracy and precision of recorded gaze points in relation to a known fixation target

Typically, the task of calibration is performed by the eye tracker or eye-gaze software, which will advance the calibration stimulus when enough data has been gathered to make the required calculations, or when a certain amount of time has passed without gaze points being registered in the vicinity of the target. Other methods of calibration are available, in which either the user or operator advances the stimulus once it is being looked at, but these are less widely used at the time of writing, with most eye tracker manufacturers preferring

the automatic calibration to standardise data collection. These other methods also have reduced utility for users with physical disability, since they require either the identification of a point of control for a switch for the user to advance the stimulus or for the operator to make a skilled judgement on when the stimulus is being foveated (Nyström, Andersson, Holmqvist, & van de Weijer, 2013).

The number of calibration points used remains the subject of current debate. It would seem logical, from a mathematical perspective, that a greater number of calibration points should result in more accurate estimation of gaze point, since the system will have more data against which to compare images during tracking (K. Holmqvist et al., 2011). Whilst this is generally the case, some users may find it difficult to maintain focus on higher numbers of calibration points owing to difficulties maintaining head position, reduced attention span or ocular-motor impairment. In fact, attempting more lengthy calibration procedures with greater numbers of points may reduce the accuracy of the calibration, since poor data samples can distort the overall results. Whilst typically developing children of pre-school age and older can calibrate accurately at nine or even sixteen points (Feng, 2011), researchers working with infants often use two or five points to ensure children remain focused during what can be a relatively uninteresting part of the process (Gredebäck, Johnson, & Von Hofsten, 2010; Von Hofsten, Dahlström, & Fredriksson, 2005). Calibration challenges faced by clinicians and researchers working with children with complex disability are discussed further in Chapter 6.

When using either eye tracking or eye-gaze control technology, best practice recommendations are that a calibration procedure should take place at the beginning of each session (Brady, Anderson, Hahn, Obermeier, & Kapa, 2014; Guestrin & Eizenman, 2006; Harezlak, Kasprowski, & Stasch, 2014). Where high precision tracking is required, it is recommended that the tracking should be regularly checked for accuracy during sessions and the calibration procedure re-run as necessary to ensure data collected remains of a high quality. Researchers have stressed the importance of documenting the calibration procedures used in eye tracking studies (Wilkinson & Mitchell, 2014).

2.8 Conclusion

This chapter has provided a definition of access to computer technology and the functions and working of eye-gaze technology. In so doing, some of the differences between eye-gaze

and other comparable direct access methods have begun to emerge. The next chapter introduces the typical development of skills that are thought to be crucial to the development of any access method, but specifically eye-gaze control.

Chapter 3

Vision and Cognition – Insights from Typical Development

This chapter describes two key developmental trajectories that inform this research, those of early vision development and the emergence of cause and effect. Whilst this chapter will discuss the typical development of these skills, the next chapter will look in more detail at the impact of cerebral palsy on their development and how difficulties in these areas might impact on the use of eye-gaze technology.

3.1 Development of Vision and Looking

Fundamental to any discussion of the use of vision for communication, or indeed the use of gaze to interface with technology, is an understanding of the typical developmental trajectory of vision. Since use of vision for communication and control requires the use of the eyes as an "output" method as well as a way of taking in information, this discussion also takes in elements of how typically developing infants begin to signal early, pre-linguistic messages through pointing and gesture.

3.1.1 Early Vision Development: 0 – 3 Months

Vision develops rapidly in the first year of life. At birth, neonates are able to identify light from dark, orienting their eyes towards large sources of light such as windows (Sharma, Cockerill, & Sheridan, 2014). They will also attend preferentially to human or other biological motion (Simion, Regolin, & Bulf, 2008) if this is large or clear enough for them to make out the characteristic features of that movement. At this stage of life, infants lack voluntary accommodation, the process by which the optics of the eye adjust to change focus, allowing the eye to retain a clear, foveated image of objects at different distances (Hainline, Riddell, Grose-Fifer, & Abramov, 1992). The focal plane of new-borns is fixed at around 20 – 25 cm, with items closer or further away appearing blurred (Hainline et al., 1992). Vision at this very early stage is therefore comparatively crude – children may show some fixation on large, highly-salient or contrasting stimuli, but new-born infants do not switch their gaze between stimuli and have difficulties disengaging (Atkinson, Hood, Wattam-Bell, & Braddick, 1992). There does, however, exist an early preference for faces or "face-like" stimuli (Dupierrix et al., 2014; Farroni et al., 2005; Simion & Di Giorgio, 2015) when these are brought close enough to neonates for them to resolve the distinctive features. Children at even the earliest

stages of development have been observed to give more attention to patterns with face-like configurations than to scrambled configurations of the same features or to non-face-like stimuli (M. H. Johnson, Dziurawiec, Ellis, & Morton, 1991). This is particularly the case if the faces have open eyes, suggesting that there is an early or innate neurological system which is primed to recognise and give extra attention to this feature (Batki, Baron-Cohen, Wheelwright, Connellan, & Ahluwalia, 2000). Crucially for the development of social skills, Farroni and colleagues showed that children at less than five days of age (M_{age} = 72 hours) have been shown to attend preferentially and for longer to images of faces with direct gaze than to images of faces with the gaze averted (Farroni, Csibra, Simion, & Johnson, 2002). This suggests that there exists at birth a preference for mutual gaze and is an early indicator of the human need to share attention with others.

In the early weeks of life, children's eyes may not always operate together and their gaze may appear to wander or drift without aim. This generally resolves by the age of around two to three months when true binocular vision then begins to develop (Braddick, Wattam-Bell, Day, & Atkinson, 1983). Observations that the eyes are not working together at this stage of development is often a cue that further investigation of a child's vision may be required (Sharma, O'Sullivan, & Baird, 2008). Making use of smooth pursuit to track moving objects is not present in the early months of life, meaning that children's attention may be "caught" by moving objects, and their eyes may move jerkily in response to a moving object in their field of vision, but they will not consistently and smoothly track these as they move (Phillips, Finocchio, Ong, & Fuchs, 1997; Von Hofsten & Rosander, 1997). This ability to smoothly track moving objects, making use of saccades to adjust the gaze trajectory and keep the object in focus, matures over the first months of life, being almost fully matured by around seven months (Luna, Velanova, & Geier, 2008)

Attention is typically fleeting and unfocused in the first three months of life, with infants not attending for more than 5 – 10 seconds (Atkinson & Braddick, 2012). Within the first month of life, as infants begin to develop some control over their eyes, head and neck, they begin to show their first purposeful looking behaviours, such as fixating on objects that are brought close to them and actively seeking out faces (Farroni et al., 2002, 2005). These early developments are aided by the emergence of an ability to switch attention between two objects (Atkinson et al., 1992) and the development of the ability to better accommodate and focus on things at different distances.

By two months of age, infants are beginning to make out more detail of the human face and are shown (Batki et al., 2000; Farroni et al., 2005) to pay particular attention to the eyes and the social cues that these can provide. By three months, children are able to hold eye-contact and are seen to intensely "study" faces for social cues and responses.

3.1.2 Vision Development from 3 – 6 Months

The following time period (roughly between three and six months) sees a huge increase in children's visual abilities and the functions for which they use their vision. Binocular vision and depth perception are becoming well developed and the maturation of the muscles and control systems within the eyes allow the child to make faster and more purposeful accommodations, leading to an improved ability to focus on one object whilst inhibiting others (Atkinson & Braddick, 2012). In addition, infants are beginning to show some understanding of the inter-related nature of eye and head movement and how these can be used together or separately to explore the visual world (Daniel & Lee, 1990; Nakashima & Shioiri, 2014). At this stage, shifting attention from one object to another, and from the background to a target object or person becomes easier (Luna et al., 2008), meaning children start to visually explore their surroundings more purposefully. Increased fixation duration during this period suggests that children are paying more attention to objects and people, making use of their vision to look at things in more detail. Attention and habituation are also developing, with children at this age showing increased attention to new or novel stimuli and experiences than to those with which they are familiar (Atkinson & Braddick, 2012). Children also demonstrate that they are able to fixate on more distant objects and are often seen to follow people around the room with their eyes. Children begin to pay greater attention to their own hands at approximately three to four months, with hand-eye co-ordination beginning to emerge, at around 4 – 5 months of age (Von Hofsten, 2007) when infants start to reach out for objects placed within their visual field, engaging for the first time in visually directed manual activities as concurrent development in the control of limbs allows.

Returning to the study by Farroni and colleagues, the investigators used event-related potentials to demonstrate significantly enhanced face processing in the brains of four-month-old infants when viewing faces with direct gaze (Farroni et al., 2002). This suggests that a special status is conferred upon direct gaze within the infant brain and that the early attention to direct gaze matures towards a system where gaze and gaze direction are given

importance within the parts of the brain involved in visual processing. Similarly, studies have shown that at around four months of age, infants begin to see the eye movements of others as potential "cues" to upcoming actions, indicating that they are beginning to privilege the movement of the eyes and representing the first emergence of gaze following in infants (Farroni, Johnson, Brockbank, & Simion, 2000; Swettenham, Condie, Campbell, Milne, & Coleman, 2003). By six months, typically developing children are generally able to follow the gaze direction of others when the object to which gaze is directed is in their field of vision (Moll & Tomasello, 2004), an early example of gaze following, which is discussed in more detail below.

3.1.3 Joint Attention and Triadic Gaze: 6 – 12 Months

Visual acuity and resolution are still maturing during this time, with children at six months able to recognise familiar adults or larger objects on the other side of a room and able to resolve a small (2.5cm) object held in their own hands (Sharma et al., 2014). By nine months, infants are able to resolve objects as small as 1mm at a similar distance. Faster habituation to new stimuli occurs by the end of the first year of life (Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004). Better recognition of patterns and the boundaries between objects emerges (Braddick & Atkinson, 2011), which has been proposed as an early milestone in the development of cause and effect skills, discussed in more detail below. At around eight months of age, typically developing babies will begin crawling, which places new demands on their use of vision, requiring increased spatial processing and the further development of hand-eye co-ordination.

Between six and twelve months, children begin to show more of the skills that are necessary for the functional use of vision. The term "functional vision" is discussed in detail in Chapter 10 of this thesis, but can be briefly defined as how a child functions in vision related activities (Colenbrander, 2003). It is during this period that joint attention begins to emerge, which is of particular interest to the work described in this thesis, since it is the precursor to pointing and an early example of children making functional use of their vision as a signalling or "output" method. Understanding joint attention and attentional cuing is an important part of social and non-social development, since it provides infants with information about what they should pay attention to and also provides their first experiences of agency over the world around them, through learning that their actions can have an effect on the mental states of others (Tomasello, Carpenter, & Liszkowski, 2007). The establishment of joint

attention begins through observation and "gaze following". Whilst some studies have shown that primitive gaze following is present from birth (Farroni, Massaccesi, Pividori, & Johnson, 2004), it is only once the visual system has matured to the point where children can determine gaze direction, switch attention between people or objects and sustain attention on a target object that children begin to show evidence of joint attention. Brooks and Meltzof worked with children at 9, 10 and 11 months of age (*n* = 96), observing their responses to adults turning their head with either open or closed eyes. The results showed that infants at 10 and 11 months followed adult turns significantly more when the eyes were open, whereas the 9 month old children showed no differentiation between the closed and open eye conditions (Brooks & Meltzoff, 2005). This suggests that a developmental shift in gaze following occurs during this time, with the emerging understanding that these have important meaning and communicative purpose and thus gaze following is often considered a response to the initiation of joint attention.

The importance of understanding and following gaze shifts to early language and communication development is underscored by the follow-up work of the same research team, who demonstrated a strong positive correlation between gaze-following behaviour at 10 – 11 months and subsequent language scores at 18 months (Brooks & Meltzoff, 2005). Similar studies have shown that, when caregivers are responsive to a child's initiation of joint attention behaviours, subsequent language and communication outcomes are better. Tomasello and Farrar, for example, showed that there was a relationship between caregiver's attention to toys to which the child attended and vocabulary size at 21 months (Tomasello & Farrar, 1986). Taken together, these findings and others like them suggest that joint attention provides an important pre-linguistic basis for the development of later communication skills.

As a result of this realisation that gaze shifts can carry meaning and can direct the attentions of others, children begin to show their own joint attention behaviours, including the development of triadic gaze. This pre-linguistic form of communication involves the child's looking at an object, switching their gaze to a communication partner and then returning their gaze to the object, or vice-versa (Hahn, Brady, & Versaci, 2019). This nonverbal behaviour is a way of directing the attention of others and has been proposed as the most communicative form of gaze, since it is the basis of the use of gaze to convey meaning (Olswang et al., 2014), comment or make requests. As with the examples of joint attention

above, triadic gaze appears to emerge as a result of observations of gaze use by people in the child's environment and emerges naturally in typically development once the required motor and visual skills have been acquired (Moore, 2013). Its development is followed rapidly in typical development by the emergence of pointing and the addition of vocalisations to clarify the message being transmitted: making the distinction between "Look at that!" and "I want that!". For children with physical disabilities, or for those who have impairments of learning or expressive language, the use of triadic gaze can assume additional importance and in some cases can provide a life-long substitute for finger pointing (Olswang et al., 2014; Pinder & Olswang, 1995).

3.1.4 Pointing and Signalling: 12 – 18 Months

The joint attention and triadic gaze skills described above are the basis for the development of the pre-linguistic skill of pointing. In typically developing infants, the first evidence of pointing emerges at around nine to fourteen months (Liszkowski, Carpenter, & Tomasello, 2007; Tomasello et al., 2007). Pointing represents the first way in which typically developing infants direct the attentions of others. Pointing is a human-specific gesture (Tomasello et al., 2007) and emerges in two distinct forms: "protoimperative" and "protodeclarative" (Bates, Camaioni, & Volterra, 1975). Protoimperative pointing emerges earlier and is used by infants to obtain something which they want or need. Protodeclarative pointing has an additional social dimension and can be thought of as "pointing to share" or pointing to direct the attention of another. This is a higher-level cognitive skill and underpins the development of other social skills. Whilst pointing skills are not discussed in detail in this work, it is worth reiterating that the use of the eyes as a possible substitute for pointing with a finger is something that is often proposed for children with movement disorders.

What the above developmental trajectory demonstrates in relation to this thesis is that visual function, functional vision, cognition and language are all linked and that, by the age of 18 months, typically developing children have acquired the physiological and functional skills needed to, in principle, make use of eye-gaze technology.

3.1.5 Assessment of Early Vision Skills

It has been noted that deficits in early vision development can provide clinicians with a key pointer that further investigation may be warranted (Sharma et al., 2014). Typically developing children in the UK undergo a series of eye examinations within the first five years

of life, beginning as part of the newborn physical examination which is carried out for all neonates within 72 hours of birth. Vision testing is then carried out again at 6 – 8 weeks and again at between 1 – 2 years as part of a health and development review, with a final check typically taking place as children start school (NHS, 2019).

3.2 Cause and Effect

The emergence of cause and effect is often cited as an important developmental milestone and its perception and understanding is a vital part of early cognitive development (Oakes & Cohen, 1990; Sharma et al., 2008). Of particular relevance to the work described in this thesis is the understanding that cause and effect is seen as fundamental to having purposeful control over a computer – with the ability to purposefully trigger an action by interfacing with the device being an important first step in the development of computer access. Established cause and effect understanding is sometimes described as a "prerequisite" for benefiting from many assistive technology devices (da Silva Ramos & Jamieson, 2019), including high-tech VOCAs, environmental control systems and computer systems used for learning. Referring to the models of assistive technology and computer access outlined in Chapter 2, it is reasonable to assume that understanding the relationship between the actions performed using the interface device and the resulting actions on screen is something that will be required before a child can be said to be "in control" of a computer for any activity. Simple technology is sometimes proposed as a way to teach or train cause and effect skills. However, this is the subject of debate, since children may be able to acquire a rudimentary, object-specific understanding of cause and effect with toys or other simple technology but transferring this to purposeful control of more complex equipment may be more challenging. Whether or not cause and effect demonstrated through simple, physical toys can be transferred or extended to understanding of cause and effect on eye-gaze technology is a key focus of this research. Since, as will be discussed in the following chapters, many eye-gaze training software packages contain activities designed to "teach" or consolidate cause and effect skills, a discussion of cause and effect, its development and how it differs when applied to a technology such as eye-gaze is warranted.

3.2.1 Defining Cause and Effect

Cause and effect is, in essence, the understanding that one action triggers or "causes" another. However, pairs of events occur commonly for which we do not perceive a causal relationship. Saxe and Carey (2006) use the example of night and day to illustrate this: night

routinely follows day, but we do not perceive or judge that night is caused by day (Saxe & Carey, 2006). It is therefore reasonable to assume that there is something that distinguishes causation from co-occurrence, coincidence or correlation. This distinction is described as the "causal impression" by the researcher Albert Michotte, whose 1963 study of the perceptions of the relationships between cause and effect are still a foundation of modern thinking about the nature and perception of causal relationships. Michotte proposed the theory that there must exist a "perceptual input analyser" within the human brain, which automatically computes the causal relationship (or lack thereof) between pairs of events (Saxe & Carey, 2006).

Michotte and those who followed his work propose that there are two elements that help determine causation: spatial and temporal. That is to say, for causation to be perceived, the event must take place at the same location and / or at the same time, otherwise a causal relationship cannot be inferred. This is described as events being either spatially or temporally contiguous (Michotte, 1963). Perceptions of spatial and temporal contiguity have been reliably tested by means of "launching events". This experimental paradigm, first trialled by Michotte, employs two-dimensional objects moving towards each other and either colliding and transferring motion from one to the other (direct launching events), colliding and moving after a temporal gap (delayed launching events), not colliding but still transferring the motion despite the spatial gap (no collision events), or not colliding and still transferring motion after a temporal gap (no collision delayed launching events). The hypothesis that all but the direct launching events would be perceived by adults as "non-causal" was supported by this experiment and by others subsequently (Saxe & Carey, 2006).

Psychologists and philosophers have built extensively on Michotte's work, proposing that the perception of cause and effect is in fact only the beginning of its understanding and that cause and effect must involve some element of active reasoning, since the brain can be temporarily fooled into perceiving a cause and effect relationship that does not really exist. This is particularly the case when events are temporally contiguous, since pairs of events occurring simultaneously are particularly susceptible to over-interpretation as causal (Cohen & Oakes, 1993; Perone, Madole, & Oakes, 2011). Therefore, it is argued, cause and effect cannot be inferred or fully understood without some knowledge or awareness of the "mechanism" by which one event causes another. It is the understanding of the mechanism that distinguishes causal events from those which merely co-occur. If the mechanism cannot

be perceived, it is argued, then we are left to reason that the events are not causal. Returning to the example of night following day, the lack of a mechanism by which day might reasonably cause night is the reason that we do not perceive these as causal. The requirement of mechanism has been described as a fundamental aspect of cause and effect and its importance to the consolidation of that skill is "an assumption beyond disproof" (Schlottmann, 2001). Knowledge and understanding of mechanism also underpin how non-spatially contiguous events can be treated as causal, for example the turning on of a light using a remote light switch.

Specific to the topic of this thesis, understanding of mechanism is particularly important, since use of an access method can be a cognitively complex task even for typically developing children; since many interfaces, such as a mouse or keyboard, are non-spatially contiguous: displaced from the actions they trigger (Light & Drager, 2007). Eye-gaze technology is arguably at an even greater remove, being non-spatially contiguous and having no transparent mechanism by which it functions.

3.2.2 Typical Development of Cause and Effect – Awareness, Observation and Prediction

In typically developing children, cause and effect is considered to emerge first as a predictive relationship. That is to say, infants are able to show an understanding or recognition that a cause produces an effect, or that there is a difference between causative and non-causative event pairings, before they themselves have developed enough purposeful movement and co-ordination to execute a causal action (Cohen & Amsel, 1998; Oakes & Cohen, 1990). Although the neurological processes through which causation is perceived were once thought to be innate, current thinking is that its emergence is as a result of the maturation of a number of sensory and cognitive processes.

In order for children to perceive events that may or may not be causal, they must first be able to perceive the objects involved in those events as separate from one another, and from the environment in which they exist (Leslie & Keeble, 1987). As discussed above, this would require vision to have developed to around the 3- to 6-month level, where children can discriminate objects and switch attention between them. In a similar vein, children would also need to recognise continuity of movement, requiring them to be able to visually track a moving object.

Results obtained by Cohen and Amsel using launching events (see Section 2.2.1), indicated that there may be a difference in the way typically developing children respond to causal and non-causal conditions. In their study, children were habituated to either direct launching, delayed launching or no contact events and then shown either the same event or one of the others. The youngest group of children (n = 36, aged 4 months) showed greater attention to causal conditions, regardless of the condition to which they had been habituated. This suggested to the authors that, at this age, children are responding on the basis of continuity of movement, since they preferentially attended to the events where this was present, rather than to the ones with either a spatial or temporal gap. The middle group of children (n = 72, 5 ½ months) showed a general increase in attention to the stimuli, as would be expected developmentally. However, those infants infants habituated either to the delay or the no collision event dishabituated significantly to the other non-causal event. The researchers suggested that these two results indicate a change in the way children are processing these events, and that children at this age are perceiving the two events separately, indicating a sensitivity to distinct events with different objects, but were not relating them. Finally, the oldest group (n = 36, 6 ¼ months) were seen to be showing emerging evidence of cause and effect, with infants habituated to a non-causal event dishabituating faster to a causal event than to another non-causal one (Cohen & Amsel, 1998). The researchers proposed that the perception of objects as separate entities and the perception of continuity of motion are both required for the perception of causality, but that these may develop separately and then combine later in development to form perception of cause and effect. The experiment described above and others like it mean that the accepted thinking is that perception of cause and effect understanding is present in infants at around 6 – 7 months.

Whilst the understanding of causal relationships is important to any access method, it is considered to be only the starting point for developing purposeful control over a system. Myrden and colleagues propose that it is at the nascence of "contingency" (the understanding of the interaction between body movements and resulting action) that might prompt clinicians to begin exploring ways of supporting children to access assistive technology (Myrden et al., 2014). It is proposed that access methods can and should be considered "even in the presence of sensory and/or severe motor impairments". The following section will outline how perception of cause and effect develops into an

understanding of contingency and in turn into purposeful control. In so doing, this discussion highlights why eye-gaze technology might be a challenging method for learning and applying contingency.

3.2.3 Typical Development of Cause and Effect – Transition to Action

Developmentally, perception of cause and effect is followed by infants learning that they themselves can initiate actions (the cause) to bring about changes (the effect). This development is crucial to the control of assistive technology, with the user needing to understand that they are in control of the device.

Experiments with very young children have demonstrated that "contingency" between body movements and resulting action can be observed at a very young age. Contingency can be summarised as the understanding that the nature of a stimuli or object is affected by the behaviour of the infant (Kushnir & Gopnik, 2007; Schlottmann, 2001). It is proposed that young children engage in a process of "contingency analysis" when introduced to new stimuli – using their vision and movement to assess the potential relationships between themselves and the new object (Trad, 1992). This analysis supports the development of cause and effect at an early stage. Rovee and Rovee (1969) designed a novel experiment to demonstrate contingency analysis, where 10-week old infants' feet were connected with a soft ribbon to a mobile hanging above their crib. The researchers observed that the response rate (number of foot thrusts) in these infants tripled within the first six minutes of exposure to the moving mobile, compared to a control group whose feet were not connected to the mobile (Rovee & Rovee, 1969). Subsequent studies (DeCasper & Carstens, 1981) have used different experimental paradigms to demonstrate similar evidence of emerging contingency in similarly young children.

However, the development of contingency into something recognisable as "active" cause and effect is limited in the early stages by infants' levels of vision and motor control. In early infancy, these are substantial constraints on how infants might translate the observed interactions between objects into "agency" – successfully controlling the manipulation of objects for themselves. In addition, and of particular relevance to this work, is the theory that the transition from prediction into action is one based on imitation and is unlikely to occur spontaneously. Bonawitz and colleagues, for example, propose that infants will not intervene on, or attempt to replicate, a predictive relationship unless they are able to see

the agent (such as an adult pushing a car towards a tower of bricks to knock it over), the events involve clear and obvious, direct contact between the objects, or the events are described to them using causal language – language specifically tailored to describe the events and to provide explicit feedback on the processes through which they occurred (Bonawitz et al., 2010). In a series of experiments, these researchers demonstrated that young children ($n = 18$, $M_{age} = 24$ months) can readily observe and learn the predictive causal relationships between pairs of events or objects, but will not themselves initiate the causal action unless one of the above three conditions (obvious agent, obvious initiation or causal language instruction) is present. Older children ($n = 18$, $M_{age} = 47$ months) were able to spontaneously transfer knowledge from observed cause and effect to having their own agency over the task.

Similarly, Yang and colleagues looked at the ability of younger infants to generalise the understanding of a physical cause and effect toy to a new toy with similar properties (Yang, Bushnell, Buchanan, & Sobel, 2013). Children of 15 months old ($n = 16$) observed an adult using two similarly designed toys, each with a different coloured control lever, one of which performed an action and the other of which did not. When presented with the toys for themselves, the children explored both levers, although they demonstrated a clear preference for the one which performed the action. When further presented with a similarly designed toy having both levers, children reliably operated the lever that they knew to perform the action. When presented with a toy of a very different design, but which still had both the same levers, this group of children did not appear to generalise the knowledge of cause and effect they had learned through experimenting with the previous toys. The researchers reasoned that children at this developmental age are sensitive to whether an action generates an effect and were not just "blindly" imitating the actions they had previously observed but were acquiring information that they could use later to perform the actions and receive the reward for themselves. However, the results of the experiment where a different toy was provided suggest that they did not generalise this knowledge.

Finally, Flynn and Whiten (2013) looked at young children's ability to generalise learning from a video of a task being performed. Children aged three years and five years watched video recordings of a toy (a transparent box with a reward inside and a multi-stage lock needing to be operated by tools to release the reward) being operated by an adult and were then given the same toy themselves. The video shown to the child was of the action being performed in

one of five conditions: (a) the whole display, including the model's hands, the tools, and the box; (b) the tools and the box but not the model's hands; (c) the model's hands and the tools but not the box; (d) only the end state with the box opened; and (e) no demonstration (Flynn & Whiten, 2013). Children's successful completion of the task was reduced in all but the first condition, irrespective of age, suggesting that the modelling of the activity by a human agent provided children with some reference about where they should put their hands in relation to the tools.

The development of "active" cause and effect, therefore appears to depend on the complexity of the activity and the information available to the child. It is likely that the causative relationship between objects or events is something that develops over the first few years of life as a result of observation and imitation, trial and error (Goswami, 2012; Sobel & Sommerville, 2009).

3.3.4 Cause and Effect and Eye-Gaze Control

Taken together, findings such as the above point to several problems when applied to children's learning to use eye-gaze technology. As discussed in the previous chapter, eye-gaze technology does not have a clear agent, even when the system is modelled. Additionally, there is no direct contact between the child and the technology. A lack of spatial contiguity between the trigger (eye movement) and the result (movement and selections on screen) may reduce the number of clues children have from which to infer the causal relationship. Considering the results presented by Flynn and Whiten, it is also important to note that eye-gaze technology is difficult to model for a child, since the movements of the eyes involved are likely to be too small to be perceived as causative. Taking this further, Yang and colleagues (2013) highlight a problem with teaching causative relationships through imitation when there is a discrepancy between the action required on an object and the effect this produces:

[challenges in inferring and learning causal relationships occur] where the action required on an object produces an effect incommensurate with the nature of the actions required to bring about that effect. For instance, one might look at a hammer and recognize its affordances, but other artefacts lack such transparent efficacy. We can press a button to activate a teakettle, but there is nothing about pressing a button that should cause water to boil.

(Yang et al., 2013, p. 511)

Eye-gaze technology may be seen as good example of this challenge in causal learning, with the smallest movements of the eyes able to generate large effects on the device, and there being nothing transparently relating these movements to the resulting action on screen. It would therefore seem reasonable to question whether developmentally younger children might have difficulty spontaneously using eye-gaze technology, owing to the lack of an explicit agent, any obvious interaction between themselves and the system and the discrepancy in affordance between the movement of their eyes and the resulting actions performed by the system. It is proposed that causal language may be the best or only remaining option for teaching this relationship but, as will be discussed further in the next chapter, children with cerebral palsy often have deficits in receptive language, which may limit their understanding of spoken instructions and hence make this a less useful strategy for this population.

3.3.5 Assessment of Cause and Effect

Previous sections have highlighted several ways in which the perception of cause and effect is tested in very young infants, although these mainly occur in research settings and are not widely used clinically. Application of cause and effect is usually assessed through observation in play-based activities, alongside structured tasks and parental report. This might include providing the child with a range of toys including toys which have a very clear action (such as pop-up toys) and observing their responses in both free and structured play (Sharma et al., 2008).

For children with physical disability, such play-based assessments may be inaccessible. Research in the fields of rehabilitation and assistive technology has suggested that the use of switch-activated toys, robots or virtual environments may offer effective ways to observe these skills in this clinical population. Cook and colleagues, for example, proposed a method of testing early cognitive skills including cause and effect, using small robots controlled by one or more mechanical switches (Cook et al., 2011). The results from this study indicated that, in some cases, children showed higher levels of cognitive function than they were able to do using standardised testing (see also Stadskleiv, 2020). The robots, the study reported, provided "a versatile tool for presentation of tasks, problems and learning opportunities" (p. 345). Clinical experience suggests that the use of switch-operated toys and other similar strategies can be an effective way to test whether cause and effect understanding is

established in young children with cerebral palsy. Similar claims are made in the supporting documentation for many eye-gaze teaching and training software packages, and it is these claims that are investigated by the early experimental work in this thesis, particularly in light of the above discussion about the nature of contingency in this technology.

3.3 Conclusion

This chapter has outlined two key developmental models that, it is reasonable to assume, will have an impact on children's use of eye-gaze as an access method. The ability to perceive items onscreen and the ability to use one's eyes as a method of pointing, signalling or selection are, it could be argued, fundamental to purposeful, functional control of an eye-gaze device. Equally, the ability to infer that one is in control of the device through the observations and understanding of cause and effect are likely to be required if use of such a system is to be made for anything other than experiential play. The following chapter introduces cerebral palsy and discusses the possible impacts of the condition on these skills, with particular reference to how these might impact on the use of assistive technology.

Chapter 4

Cerebral Palsy

4.1 Defining Cerebral Palsy (CP)

Cerebral palsy (CP) describes a non-progressive and persistent neurodevelopmental disorder, arising from damage to the developing foetal or infant brain (Bax et al., 2005). Whilst early definitions of the condition focused on the primary impairments of movement and posture that characterise the condition, contemporary definitions expand upon this, noting that the focus on movement and posture does not give sufficient prominence to the non-motor neurodevelopmental disabilities of performance and behaviour that commonly accompany this description (Rosenbaum et al., 2007). Additionally, with the widespread adoption of the *International Classification of Functioning, Disability and Health* (ICF, World Health Organisation, 2001a), more recent definitions of CP specify that the disorder causes restrictions in activity and participation, with individuals diagnosed with CP needing support, adaptation or modification of tasks or the environment. This is consistent with the ICF's focus on evaluating the functional consequences of ill health or disability.

In 2007, the Surveillance of Cerebral Palsy in Europe (SCPE) group conducted a Europe-wide investigation into locally and nationally held CP registers, looking at the definitions used and the prevalence of the condition. This survey, the largest of its kind in Europe, identified that there was considerable variation in the definitions of CP used across the continent, with the inclusion and exclusion criteria used by clinicians, varying between countries and even from centre to centre within them (Surveillance of Cerebral Palsy in Europe (SCPE), 2007). Since the condition is defined by clinical criteria, and since the aetiology, pathology and prognosis of the condition are highly variable, CP is frequently referred to as a "clinical description", rather than a diagnosis (Blair, Cans, & Sellier, 2018; Colver, Fairhurst, & Pharoah, 2014) and is therefore much harder to define precisely. Owing to variance in clinical presentation and severity of impairments, people with CP represent a heterogeneous population. The SCPE proposed that any definition should include five "key elements":

- CP is a group of disorders i.e. it is an umbrella term;
- it is permanent but not unchanging;
- it involves a disorder of movement and / or posture and of motor function;

- it is due to a non-progressive interference / lesion / abnormality;
- this interference / lesion / abnormality is in the developing / immature brain.

<div align="right">(2007, p. 818 – 819)</div>

Whilst the core feature of CP is the movement disorder, modern classifications include accompanying, comorbid disorders of sensation, cognition, communication, perception, behaviour and seizure activity (Bax et al., 2005). These comorbidities are discussed in more detail in Section 4.5 below.

4.1.1 Prevalence of CP

Cerebral palsy is the most common physical disability in childhood. As noted by the SCPE, reports of the prevalence of the condition vary depending on the method used to generate the figures, however a recent systematic review (Oskoui, Coutinho, Dykeman, Jetté, & Pringsheim, 2013) placed the overall prevalence at 2.11 per 1,000 live births. Some studies estimate the figure to be higher, up to 3.6 per 1,000 live births (Christensen et al., 2014; Yeargin-Allsopp et al., 2008). Whilst prevalence is declining in developed countries such as Australia and much of Europe (Novak et al., 2017), globally the prevalence has remained constant in recent years (Oskoui et al., 2013), despite the increased survival rate of pre-term infants who are at greater risk. However, studies have pointed to a decrease in the prevalence and severity of the disability in babies carried to term (Sigurdardóttir, Thórkelsson, Halldórsdóttir, Thorarensen, & Vik, 2009).

4.2 Identification and Diagnosis

Cerebral palsy is typically identified between 12 and 24 months of age, although clinical signs of the condition frequently appear before this time (Michael-Asalu, Taylor, Campbell, Lelea, & Kirby, 2019) and it has been proposed that the condition can be identified at 5 months or even earlier (Novak et al., 2017). Given the multiple and varied causes of CP, the disorder is diagnosed on clinical signs, rather than aetiology (MacLennan et al., 2019), and children who meet the criteria for a diagnosis of CP will typically have an observable movement disorder: where the quality of a child's movement or motor function is reduced or abnormal, or where motor activities are substantially below those expected for their chronological age. The confirmation of the description of CP is made either through abnormal results on a magnetic resonance imaging scan – where lesions or damage to the brain are visible – or through

abnormal results from neurological assessment by experienced clinicians. These assessments may be informed by clinical history-taking indicating the presence of clinical risk factors for the condition (Novak et al., 2017).

4.3 Assessment and Classification of Cerebral Palsy

Reflecting the complex nature of the condition, classification and categorisation of CP is a complex task, with various systems and methods proposed to describe the presentation of the condition (Colver et al., 2014). A number of standard classification systems exist which focus on the aetiology or biomedical description of a person with CP (the site of the brain lesion, the type and severity of the movement disorder, degree of muscle tone and the involvement of limbs). Such classifications can require a high level of specialist clinical knowledge, the use of complex equipment such as magnetic resonance imaging (MRI) or standardised assessment tools. As a result, they are most useful in the assessment diagnosis of CP; providing a description of an individual for clinical care, particularly when transferring from one area or specialism to another. Typically, classification of CP has used the neurological terms for describing a central motor disorder: spastic, dyskinetic, ataxic or mixed (Surveillance of Cerebral Palsy in Europe (SCPE), 2007). These are often referred to as the "clinical subtypes" of CP and are often used in conjunction with topographical classifications of the limbs which are affected by the movement disorder; including diplegia, triplegia, tetraplegia, quadriplegia or hemiplegia (Graham, 2005). Subjective measures of severity such as mild, moderate and severe are also sometimes used (Paulson & Vargus-Adams, 2017).

Classifications by type of motor disorder and topography have been shown to be unreliable for predicting the overall presentation of any one individual within that subtype (Graham, 2005), although such classifications can in some cases predict the likelihood of specific impairments, such as level of motor function (Shevell, Dagenais, & Hall, 2009) or the likelihood of vision disorders (Dufresne, Dagenais, & Shevell, 2014).

It has been observed (Bax et al., 2005) that assigning individuals with CP to distinct groups is therefore not as simple as choosing one characteristic as the basis for classification. As a result, no single classification system has emerged as definitive and certain characteristics or combinations of characteristics may be chosen to describe participants in clinical trials or research studies, depending on the purpose of the classification.

4.4 Functional Classification

Whilst the classification of CP into subtypes is useful to clinicians making diagnoses or decisions about some aspects of management, more recent classification systems for CP have tended to move away from medical description and towards scales based on "functional classification": classification on the basis of an individual's abilities and limitations in a specific aspect of life such as mobility, eating and drinking or expressive language. Such functional classification scales capture the everyday functioning of a person in a way which diagnostic labels cannot (Cockerill, 2015).

These scales are based on the *International Classification of Functioning, Disability and Health* (World Health Organisation, 2001b), which has been previously discussed in Chapter 2, and which conceptualises disability as the result of a complex inter-relationship between the health condition and environmental (personal and contextual) factors. Teams developing functional classification systems point to their being distinct from assessments or tests, being used for descriptive rather than diagnostic purposes, whilst acknowledging that they may be complimentary to a detailed and holistic assessment of an individual (Hidecker et al., 2011; Palisano et al., 1997). It has been proposed that functional classification systems describe "performance" (a person's usual activity) rather than "capacity" (what a person can do at their best), meaning that the focus is shifted from a person's deficits and towards their abilities (Rosenbaum, Eliasson, Hidecker, & Palisano, 2014). Since functional classification systems do not seek to explain why a person has a particular presentation, it is often the case that standardised assessment measures and functional classification systems are used alongside one another (S. M. Reid, Meehan, Reddihough, & Harvey, 2018).

Over the past twenty-five years, this shift towards the functional classification of CP has resulted in scales which can be used to describe an individual's gross motor function (Palisano, Rosenbaum, Bartlett, & Livingston, 2007; Palisano et al., 1997), manual ability (Eliasson et al., 2007; Eliasson, Ullenhag, Wahlstrom, & Krumlinde-Sundholm, 2015), eating / drinking ability (Sellers, Mandy, Pennington, Hankins, & Morris, 2014), speech (Pennington et al., 2013), communication (Caynes et al., 2019; Hidecker et al., 2011) and visual functioning (Baranello et al., 2019). A de facto template for the production of functional classification systems has emerged, with most adopting a five-point ordinal scale with accompanying brief descriptors or titles for each level (see Table 4-1), alongside a more

detailed description of the functional abilities and limitations likely to be present at each. Accompanying literature and guidance notes will also outline the distinctions between the levels as a helpful aid to clinicians.

Functional classification scales are used to describe all participants with CP involved in the activities described in this thesis. The reasons for this are twofold: firstly, as has been discussed previously, they are more helpful in describing a child's overall performance. Since no one clinical characteristic can be used to usefully classify children with CP, functional scales are more appropriate to provide a working description of the children participating in the activities. Secondly, as will be discussed in more detail in the chapters that follow, a wide variety of children with CP are considered by clinicians and educators to be candidates for eye-gaze technology. Consideration of this intervention is likely not linked to diagnosis or clinical subtype, but it is not unreasonable to assume that the children being trialled with this technology are those with more severe levels of motor impairment, more difficulties with manipulation of objects and greater difficulties with speech and functional communication. This is due to the perception – discussed previously in Chapter 2 – that eye-gaze can offer a direct access method to children whose movement disorders might previously have prohibited the identification of a reliable point of control for direct access to AAC or other computer-based activities (Smith, 2019).

Three functional classification systems are used to describe the children with CP participating in the experimental sections of this thesis, each of which are described below. Since each classification offers brief, summary descriptors for each level, these are presented together in Table 1.

The *Gross Motor Function Classification System* (GMFCS) comprises two functional rating scales for children aged below 2 years and children aged 2 - 12 years. The five-point rating scale describes a child's self-initiated movement, with an emphasis on sitting, transfers and mobility and the rating system focuses on determining which level best represents current abilities and limitations in gross motor function (Palisano et al., 2007). In common with other functional classification systems, the GMFCS is designed to reflect the usual performance of a child or young person across all environments.

Table 1 - Brief Description of the Levels of the GMFCS, MACS and CFCS

Classification System	Level	Descriptor *
Gross Motor Function Classification System (GMFCS) (Palisano et al., 1997; Palisano et al., 2007)	I	Walks without limitations
	II	Walks with limitations
	III	Walks using a hand-held mobility device
	IV	Self-mobility with limitations; may use Powered Mobility
	V	Transported in a manual wheelchair
Manual Ability Classification System (MACS) (Eliasson et al., 2007)	I	Handles objects easily and successfully
	II	Handles most objects successfully but with somewhat reduced quality and / or speed of achievement
	III	Handles objects with difficulty; needs help to prepare and / or modify activities
	IV	Handles a limited selection of easily managed objects in adapted situations
	V	Does not handle objects and has severely limited ability to perform even simple actions
Communication Function Classification System (CFCS) (Hidecker et al., 2011)	I	Sends and receives with familiar and unfamiliar partners effectively and efficiently
	II	Sends and receives with familiar and unfamiliar partners but may need extra time
	III	Sends and receives with familiar partners effectively, but not with unfamiliar partners
	IV	Inconsistently sends and / or receives even with familiar partners
	V	Seldom effectively sends and receives, even with familiar partners

* Full versions of the classification systems and instructional materials can be found at:

GMFCS: https://canchild.ca/en/resources/42-gross-motor-function-classification-system-expanded-revised-gmfcs-e-r

MACS: https://www.macs.nu/

CFCS: http://cfcs.us/

The *Manual Ability Classification System* (MACS) is designed to classify how children with CP (aged 4-18 years) use their hands when handling objects in daily activities (Eliasson et al., 2007). It also includes an additional classification for younger children (1 – 4 years), entitled Mini-MACS (Eliasson et al., 2015). The system describes manual ability and upper limb function. The MACS is a helpful classification system when considering access methods for a

child with CP, since the upper limbs and hands are often the first control point explored by clinicians looking to facilitate access to a computer or VOCA for a child.

The *Communication Function Classification System* (CFCS) allows functional description of a child's communication, taking into account all communication modes and channels (Hidecker et al., 2011). The CFCS views communication as a whole, focusing on the transmission and receiving of messages.

With the establishment of three functional classification for gross motor, fine motor and communication skills, it has seemed logical to many researchers that the scales should be used together, in order to provide a better description of the functional profile of a child with CP, reflecting "real world" performance. Several studies have demonstrated that the GMFCS, MACS and CFCS complement one another in the description of a child with CP (Compagnone et al., 2014; Hidecker et al., 2012).

Of relevance to the work in this thesis is the understanding that children considered for eye-gaze technology are likely to be those at the higher end of all three of these rating systems, where impairment is most severe. Likely candidates will be children who cannot mobilise independently, who have difficulties producing clear speech or conveying messages and whose upper limb control precludes the use of switches or conventional pointing devices.

4.5 Cerebral Palsy and Comorbidity

Children with CP often present with other disorders or impairments, referred to as "comorbidities", which may be caused by the same initial disturbances that caused the central motor disorder or may occur as a direct or indirect consequence of this. As cited above, these impairments may include those of sensation (vision, hearing, and other sensory modalities), cognition (both global and specific cognitive processes may be affected, including attention), communication (expressive and receptive skills, as well as social interaction), perception (the capacity to incorporate and interpret sensory and/or cognitive information may be impaired) and behaviour (such as features of autism, ADHD, mood and anxiety disorders) (Bax et al., 2005). Findings from a systematic review (Odding, Roebroeck, & Stam, 2006) indicate that, dependent on subgroup, 25 - 80% of children with CP have at least one additional impairment. The National Institute for Health and Care Excellence (NICE) guidelines on the assessment and management of CP in children and young people recognise

that such comorbidities add to the heterogeneous nature of the description. The guidelines also note that many of these comorbidities can go unrecognised or unmanaged, as the focus of clinicians is frequently on management of the primary motor disorder (National Institute for Health and Care Excellence (Great Britain), 2017).

Data on the comorbidities of children with CP can be hard to find. In some cases, they are recorded in local or national registers (Surveillance of Cerebral Palsy in Europe (SCPE), 2007) or they are described in research studies. A recent systematic review conducted by the Cerebral Palsy Alliance Research Institute in Sydney, Australia (Novak, Hines, Goldsmith, & Barclay, 2012) identified 30 papers with moderate to high quality data on impairments, diseases, and functional limitations co-occurring with CP. The systematic review indicated that 26% of children with CP had abnormal behaviour, 35% had epilepsy (with 24% having active epilepsy not currently controlled), 4% had severe hearing impairment or were diagnosed as deaf and 11% were functionally blind. Regarding communication, which is discussed in more detail below, 23% of children with CP were non-verbal. Almost half of children with CP (49%) had a description of intellectual disability. A recent prevalence study (Christensen et al., 2014) noted the co-occurrence of autism in 6.9% of children with CP, although such prevalence figures are often debated owing to the difficulty children with CP have participating in standard instruments for the assessment of this condition (Price, 2017).

Other studies have reported that co-occurring impairments are particularly prevalent in the population of children who are more severely affected physically and who are non-speaking. Indeed, a study (Sigurdardóttir et al., 2009) has demonstrated that 88% of non-speaking children with CP presented with two or more associated impairments, compared with only 18% of speaking children with the condition. Similarly, Dufresne and colleagues noted that the prevalence and severity of visual impairments increased with the severity of a child's motor disorder (Dufresne et al., 2014). Venkateswaran and Shevell (2008) looked at four comorbidities (visual impairment, hearing status, feeding difficulties and epilepsy) in children with one particular subtype of CP - spastic quadriplegia. This study found all four comorbidities to be quite prevalent in this population (Venkateswaran & Shevell, 2008) and that the frequency of all four increased with higher GMFCS levels. The authors of this study draw particular attention to the impacts of comorbidity, noting that their presence can dramatically increase the care needs of a child and can impact the overall quality of life for both the child and the family (Blair et al., 2018; Blair & Watson, 2006). Ensuring that

comorbidities are accurately described and properly acknowledged can therefore support families in accessing suitable support and resources for their child, thus minimising the risk of secondary complications and reducing the impact of caring for a child with disabilities.

The following sections provide an overview of the literature and current understanding for three comorbidities which are highly relevant to this project: cognition, vision and communication.

4.6 Cerebral Palsy and Cognition

Knowledge of the cognitive development of children with CP is lacking. This is due in part to a lack of longitudinal studies: in a recent narrative review paper, Stadskleiv found that only 9 out of 81 papers included had a longitudinal design, suggesting that there is a poor understanding of the developmental trajectories of this group (Stadskleiv, 2020).

The existing research suggests that many children with CP present with some degree of cognitive impairment. Recent figures from the Australian Cerebral Palsy register indicate that 45% of children with CP have some degree of intellectual impairment and that 19% present with a moderate to severe degree of impairment (Australian Cerebral Palsy Register, 2018). Similar prevalence figures are reported in the NICE guidelines, where a figure of 48% is quoted for the presence of some degree of cognitive impairment across the CP population (National Institute for Health and Care Excellence (Great Britain), 2017). Severity of intellectual impairment is associated with motor ability across all subtypes of CP, with Delacy and colleagues finding moderate to severe intellectual impairment in $7 - 15\%$ of children with GMFCS levels I and II, compared to 55% of children at GMFCS V (Delacy & Reid, 2016). Findings such as this need to be set in the context of the reported difficulty of assessing this group of children (Stadskleiv, 2020), particularly those with greater degrees of gross and fine motor impairment. This is discussed in greater detail below, and in Chapter 6.

Cognition has been shown to be independently associated with language impairment (Mei et al., 2016) and the presence of intellectual impairment has been shown to be closely related to impairments of receptive language (Vos et al., 2014). Cognitive impairment is particularly associated with the comorbid presence of epilepsy (Sigurdardóttir et al., 2009; Vargha-Khadem, Isaacs, Van Der Werf, Robb, & Wilson, 1992), particularly when these seizures are early onset or remain uncontrolled for long periods of time.

The presence of cognitive impairment in children with CP can affect functional performance in almost all areas of life. Studies have shown that severe cognitive impairment is linked to mobility, gross and fine motor function (Dalvand, Dehghan, Hadian, Feizy, & Hosseini, 2012) and development of language (Himmelmann, Lindh, & Hidecker, 2013). Better cognitive functioning is correlated with increased participation in children with CP (Bøttcher, 2010; Imms, 2008; Law et al., 2004), with children with higher levels of cognitive ability showing better social interaction and being more likely to use alternative methods of communication where speech is impaired or absent. Of perhaps greatest relevance to this study is the link between cognitive impairment and vision, discussed below, and the impact that cognitive impairment has on learning new skills. Children with cognitive impairments are likely to need individually tailored learning approaches (Bøttcher et al., 2015) which take into account the impact of their learning disability, but which also acknowledge the impact that cognitive impairments may have on engagement, behaviour, fatigue and emotional regulation (Whittingham, Sanders, McKinlay, & Boyd, 2014).

It is worth noting at this stage that difficulties exist in measuring intellectual impairment in children with CP. It is often raised that methods of cognitive assessment for this group of children is more challenging due to the impairments of motor, vision and speech skills (Bøttcher, 2010). In the aforementioned review paper, Stadskleiv found evidence that the cognitive abilities of children with more severe motor impairment (GMFCS IV and V) were frequently assumed rather than assessed, with this assumption frequently being attributed to the inaccessibility of standard testing materials (Stadskleiv, 2020). Sherwell and colleagues summarise the challenges in administering standard intelligence tests with this population of children; pointing out that even the smallest degree of motor or speech impairment can negatively impact the results of assessments (Sherwell et al., 2014). Standardised measures of cognition often lack reliability data or normative data specific to this population (Yin Foo, Guppy, & Johnston, 2013), and many rely on object manipulation, timed completion or verbal responses, which may be more difficult or impossible for this group of children. Where assessments were adapted for the use of children with more severe motor impairment, severe cognitive impairment was shown to run at a lower rate than typically reported in the literature, suggesting the cognitive abilities of this population may be underestimated by the way in which they are tested (Stadskleiv, 2020). Challenges in the assessment of children with CP are discussed in more detail in Chapter 6.

4.6.1 Impact of Cerebral Palsy on Cause and Effect

In the previous chapter, the importance of consolidated cause and effect understanding for control of activities was noted. It has been observed (Cook et al., 2011) that cause and effect skills are likely to emerge differently in children with CP and similar motor disorders. In particular, the transition from perception of causal relationships to the application of this understanding to interactions in the real world may be impacted upon by the constraints that their movement disorder places on their ability to explore the world and to interact with objects (Cook et al., 2011). Few studies look in any detail at the profile of very early cognitive skills such as cause and effect in this population, however it is worth noting that computer-based assessments, assessments involving robots or virtual reality settings are increasingly proposed as methods to provide better insight into these early cognitive skills in children with more severe motor impairments (Cook et al., 2011; Encarnação et al., 2014; D. Reid, 2004). It has also been proposed (E. Holmqvist, Thunberg, et al., 2017) that eye-gaze controlled devices can provide a way for children to explore cause and effect at an early level and to inform their understanding that they can have influence on the world around them.

4.7 Cerebral Palsy and Vision

It is well established that children with CP are more vulnerable to damage to all aspects of the visual system (Deramore Denver, Adolfsson, Froude, Rosenbaum, & Imms, 2017; Deramore Denver et al., 2016; Jan, Lyons, Heaven, & Matsuba, 2001; Park, Yoo, Chung, & Hwang, 2016). These include refractive errors, reduced acuity, ocular-motor disorders, malformation of the eyes, as well as the group of disorders associated with the visual systems and pathways of the brain, which are often referred to as cerebral visual impairments (van Hof-Van Duin et al., 2008).

Several of the papers discussed in earlier sections describe the frequency and severity of visual impairment in this population group. Venkateswaran and Shevell found visual impairment to be the most common comorbidity in the group of children recruited to their study, reporting some degree of visual impairment in 66 of the 83 children included in their study (80%) with 17 (21%) presenting as blind. In that study, visual impairment was more common in children with higher GMFCS levels (Venkateswaran & Shevell, 2008). Dufresne and colleagues noted some degree of visual impairment in almost half (49.8%) of children (*n* = 214) included in their study (Dufresne et al., 2014). Impairments noted included

strabismus, refractive error or severe visual loss. Both frequency and severity of visual impairment were found to increase with a child's GMFCS levels and were most common in non-ambulant children (GMFCS IV and V), where 80% of children had some degree of impairment.

More recently, studies have begun to look not only at the levels of visual impairment in this group of children, but also at their levels of visual ability or their functional use of vision (M. Clarke et al., 2017; Colenbrander, 2003; Deramore Denver et al., 2017, 2016; Sargent et al., 2017). This construct, referred to as "functional vision" or "visual ability", arises from the observation discussed above that children whose motor disorders limit both their use of clear speech and their ability to accurately point to pictures, objects or symbols may be more reliant on the use of their gaze for communication, requesting and interaction. It has been observed that there is a lack of clarity both on the terminology used to describe this use of vision (Sargent et al., 2013) and on the methods used to measure or describe how children are making use of their vision in this way (Deramore Denver et al., 2016). Functional vision is the focus of Chapter 10 of this thesis, where its measurement and impact are discussed in greater detail.

4.8 The Impact of Cerebral Palsy on Communication

Impairments of receptive and / or expressive communication can be present, to varying degrees, in any type or severity of CP (Australian Cerebral Palsy Register, 2018; Novak et al., 2012). Estimates of the prevalence of communication impairment vary across the literature. A CP register review carried out by Parkes and colleagues using the Northern Ireland Cerebral Palsy Register (NICPR) in 2010 indicated that half the population of children with CP will have one or more impairment of oro-motor function, communication or both (Parkes, Hill, Platt, & Donnelly, 2010). In that study (n = 1,357), 36% of children presented with motor-speech problems and 46% had communication impairments (excluding articulation defects). These figures led the authors to conclude that impairments of oro-motor function and communication are common in the group of children with CP, also noting that communication impairments were not related to any particular clinical subtype. The authors also highlighted that these impairments were significantly related to poorer gross motor function (as reported using GMFCS levels) and greater levels of cognitive impairment – with children having an IQ of less than 70 being significantly more likely to present with communication impairment.

Similarly, a register study conducted in Sweden (Himmelmann et al., 2013) showed that 100% of children (*n* = 19) with severe cognitive impairment were described as being at CFCS level V (Seldom effective sender and receiver even with familiar partners). In this study, children's level of communicative ability was found to be strongly correlated with gross motor function, with 82% (*n* = 14) of children at GMFCS level V also being at CFCS level V. Similar results were observed for upper-limb skills.

The impact of CP on the functions of a child's communication has also been well documented. Studies have shown that non-verbal children with a description of CP tend to take a more "passive" role in communication (Pennington & Mcconachie, 1999, 2001), initiating less and tending to act more as a respondent to partners' questions. Non-verbal children with CP also take fewer conversational turns, use fewer pragmatic functions (Pennington, 1999) and often only respond using yes and no answers to closed questions posed by adults (Light, Collier, & Parnes, 1985; Pennington et al., 2004). These observations should be taken with the caveat that much therapeutic intervention and indeed much parent-child interaction between caregivers and children with CP, tends to focus on the teaching of requesting and responding behaviours, or on specific aspects of receptive language (Pennington et al., 2004).

4.8.1 Cerebral Palsy and Receptive Language

Research describing the receptive language abilities of children with CP is scarce in comparison to studies looking at their speech or other expressive language modes (Mei et al., 2016). Mei and colleagues conducted a population-based study of five- and six-year olds with CP (*n* = 232), looking at receptive and expressive language ability. The study demonstrated that receptive language impairments commonly co-occur with impairments of expressive language – as was the case in 44% of the children included in their study – and isolated occurrence of either is infrequent (Mei et al., 2016). The researchers did not however observe greater impairment within any one linguistic subdomain, indicating that this group of children present with a general deficit in receptive language. Other studies looking at the understanding of vocabulary and grammatical structure in children with CP suggest that problems with these areas of receptive language occur more frequently with greater severity of movement disorder (Parkes et al., 2010; Pirila et al., 2007). Clinical

experience suggests that children with CP may have comparatively strong understanding of single word vocabulary, in comparison to their understanding of grammatical structure.

Receptive language difficulties in children with CP have also been shown to be linked to the presence of intellectual impairment, with children and adolescents without co-occurring intellectual impairment showing fewer difficulties with receptive language (Pirila et al., 2007; Vos et al., 2014).

The impact of receptive language impairment, particularly more severe impairment, can be profound. Impairments in the understanding of language impact on the development of social relationships (E. Holmqvist, Derbring, & Wallin, 2017) and on general learning, academic achievement and the development of literacy (Vos et al., 2014). Receptive language also plays a pivotal role in the use of AAC, which is something to which many children with CP will be exposed during their early years. Accurate assessment of receptive language ability is important to ensure that any such intervention is appropriately pitched, making sure it is delivered in a way that the child can understand (M. Clarke et al., 2016; Sevcik, 2006).

4.8.2 Cerebral Palsy and Speech

Children with CP can present with severe limitations in oro-motor ability, which can in turn impact on the use of speech. The disorders of movement which characterise CP may impact on any and all speech systems, including on the muscles involved in controlling respiration and articulation (Pennington et al., 2013). As a result, the speed and intelligibility of speech in this group of children can be highly variable, with descriptions of dysarthria (unintelligible speech) and anarthria (absent speech) being common. Recent statistics from the Australian Cerebral Palsy Register reveal that 63% of children with CP present with some degree of speech impairment at 5 years old (Australian Cerebral Palsy Register, 2018), with around 24% of children being classified as non-verbal. Similar results are reported in other studies (e.g. Mei et al., 2016) and researchers have also highlighted that the likelihood of severe speech impairment increases at higher GMFCS levels (Novak et al., 2012; Sigurdardottir & Vik, 2011).

4.8.3 Cerebral Palsy, Expressive Language and AAC

The population of children with CP who have greater degrees of motor impairment (GMFCS levels IV and V) are likely to face significant barriers to their communication with others (M.

Clarke et al., 2016). Vos and colleagues (2014), for example, showed that impairments of expressive language were linked to the type and severity of the movement disorder, with expressive communication development (specifically speech) being typically more advanced in unilateral spastic CP than in bilateral CP (Vos et al., 2014).

Since the above sections have demonstrated that these children are likely to have greater difficulty using clear speech, this group of children can be heavily reliant on the use of communication modalities such as vocalisations and kinesic resources such as gesture, pointing, facial expression or the use of directed gaze (M. Clarke et al., 2016). Whilst these methods may be helpful in responding to questions from a communication partner or signalling important wants and needs, they provide very limited opportunities for self-expression, and almost none for making use of more complex linguistic forms. Depending on the type and severity of their motor impairment, children with CP can also be precluded from the use of a full sign language as an effective mode of communication, although they may still use a range of approximated signs alongside other communicative modalities (M. Clarke et al., 2016). For this reason, children with CP are often considered to be candidates for AAC, as discussed in the introduction this thesis. Particularly where greater degrees of physical impairment are present, the use of high-tech systems is often proposed as a way to support children in accessing communication resources – using technological solutions to compensate for the difficulties that they may experience with accurate pointing or control, in accordance with the concept of transferring functions from the Human to the Assistive Technology sections of the HAAT model (see Chapter 2). Assistive technology can overcome a variety of physical disabilities through the use of alternative access and control methods, as well as encoding language concepts in ways which are easier to understand. However, since it is likely that children with the greatest need for high-tech AAC will also be those who are most physically impaired (Sigurdardottir & Vik, 2011), and since the literature summarised above indicates that these children are most at risk of cognitive impairment which may mean they face greater obstacles to learning new skills, there is a need to consider how these children might begin to learn the control methods needed to make best use of high-tech AAC.

4.9 Conclusion

This chapter has introduced the clinical population of children with CP who are the focus of this work. The literature discussed provides an overview of some of the impairments of

vision, cognition and communication that may potentially impact on their use of eye-gaze technology. One consistent theme across the literature summarised here is the need for robust, individualised assessment of children's skills. Vos and colleagues (2014) observe:

In order to prevent under- or overestimation of the child's level of communication skills, accurate identification of the child's level of communication skills is vital […].

(p. 7)

The need for accurate assessment of this clinically complex population of children may mean that clinicians and researchers need to look beyond the use of standardised testing materials and towards adapted or novel methods of assessment. This is discussed in greater detail in the next two chapters. In the summary of her review paper, Stadskleiv (2020) notes:

Tests need to be adapted, for example using eye- gaze technologies, so that cognitive functioning can be reliably assessed, and not only assumed, in the most severely motor-impaired children.

(p. 287)

The experimental chapters of this thesis seek to contribute to the discussion around the importance of clinicians having a robust understanding of children's skills when making choices about assistive technology, and particularly about eye-gaze. The experiments which follow examine the presentation of these skills in this group and look at the insights that can be gained using eye-gaze and eye tracking technologies. These is an emphasis on exploring how vision and cognition may impact on eye-gaze use. In so doing, it is hoped that this work will assist clinicians in managing the expectations around progress with this technology and ensure that children's individual patterns of strengths and needs are recognised when making these decisions. The next chapter introduces some of the concepts that first motivated this work by discussing how eye-gaze technology has been positioned as a panacea for all access needs and, in some cases, as a unitary skill which is learnable by all children.

Chapter 5

Current Issues in Eye-Gaze Technology

5.1 Introduction

Clinicians working to select an appropriate access method for a child with motor impairment are often faced with complex decisions. The need to provide an access system that is specific to the individual is a process which involves careful assessment and consideration of a broad range of physiological, sensory, environmental and personal factors. However, a paucity of research evidence exists to support clinicians in making these decisions, meaning they must often rely on previous experience or smaller research projects such as case studies or case series reports (Griffiths & Addison, 2017; Higginbotham et al., 2007; Light & McNaughton, 2013; Myrden et al., 2014).

Tai and colleagues (2008) highlighted that, whilst research into the selection and use of access methods is increasing, this evidence is often difficult to find and access, as it comes from a broad range of fields including disability, human computer interaction and rehabilitation engineering (Tai et al., 2008). In the subsequent years the relatively small number of review articles examining issues of access highlight a paucity of research evidence in the field (Elsahar, Hu, Bouazza-Marouf, Kerr, & Mansor, 2019; Fager et al., 2012) .

This is particularly the case when considering eye-gaze control technology for children. The fields of AAC and assistive technology face several new challenges as this technology develops, and it is these that are discussed in more detail in this chapter. Firstly, there is a risk that assumptions will be made about the skills needed to access the technology or the ease with which children will acquire these skills. Such assumptions make it difficult for clinicians to manage the expectations of those who perceive this new technology as a panacea or as a way to "unlock" previously unheeded abilities which have been hidden behind access difficulties. This is especially challenging when it may seem logical to some that eye movement and the ability to orient gaze is all that is required to access and control this technology. Secondly, a gap exists between research and practice, which has emerged as a result of its desirability, leading in turn to clinical implementation of this new technology without a robust evidence base to support decision-making. Finally, the past few years has seen a proliferation of programmes to "teach" the skills needed to control eye-gaze

technology, which are key motivator of this research. The fact that many of these packages begin with very basic experiential interactions with the technology and progress towards the use of complex communication software only serves to compound this issue – tacitly presenting the idea that all children will follow a similar trajectory in the acquisition of these skills and that the use of high-tech AAC is an appropriate and achievable goal for all children through the medium of eye-gaze technology.

The following sections set out this author's motivation to carry out this research, based on clinical experience, and also discusses some key rationale for the work and frames the questions that subsequent chapters will address.

5.2 Risk of Clinical Assumptions

Robust assessment of children's skills is important to underpin decisions made about access methods or appropriate assistive technology interventions. Previous chapters have highlighted that the cognitive load of access methods are often under-appreciated, with more attention paid to the physical requirements of the access method, rather than its cognitive demands (Marina et al., 2012). It remains the case that factors such as vision and cognition are not always assessed or reported in the group of children with movement disorders (Sargent et al., 2017). The previous chapter highlighted the findings from the narrative review by Stadskleiv, who noted that cognitive skills in particular were often assumed rather than assessed in this population (Stadskleiv, 2020).

Of particular relevance to consideration for eye-gaze technology, vision is often not well described by therapists referring to services providing AAC and assistive technology (Sargent et al., 2013, 2017). This is also the case in the published literature, with a ten-year review of efficacy studies by Bedrosian noting that only 50% of studies reported participants' levels of hearing and vision, despite their clear importance to the use of AAC (Bedrosian, 2003, p. 70).

Whilst clinicians will often report on correctable refractive errors (such as whether or not a child wears glasses), functional descriptions of a child's *use* of vision or their observed responses to visual stimuli are not readily forthcoming (Deramore Denver et al., 2017). Clinical experience suggests that these skills are often not observed or commented on by clinicians considering children for eye-gaze technology, although it would seem logical that they may have an impact on the way in which children make use of this technology. One

study (Sargent et al., 2017) has suggested that parents can act as reliable reporters of their child's use of vision if asked a series of structured questions, however such descriptions are seldom included in referral information or brought up by therapists in clinical discussion. Rather, there appears to be an assumption that children's use of vision, discussed in detail in Chapter 10 of this thesis, will develop naturally or can be improved by intervention. There seems to be an assumption that most children with movement disorders will be able make intuitive use of vision to communicate or control eye-gaze technology, although this may not in fact be the case.

Similar assumptions are often made about a child's cognition. Children with physical disabilities are often considered difficult to assess (Gumley et al., 2011) and may not be able to access standardised assessments, particularly where this requires the effective manipulation of objects, giving verbal responses or accurately pointing to pictures (Geytenbeek, Heim, Vermeulen, & Oostrom, 2010; Stadskleiv, 2020). Since it is known (see Chapter 4) that children with CP may present with an uneven developmental profile, there is potential for children's cognition to be under- or overestimated if it is inferred from their diagnosis, clinical description or other skills.

In the absence of robust ways of assessing this population, clinicians may be tempted to assume levels of ability in children, or to infer abilities from observing general performance. In the early chapters of this work the risks associated with presumed competence were outlined, but there is an equal risk that children's skills may be underestimated if they are inferred from their performance in activities that may be more difficult for them.

All of the above clinical assumptions arise from the idea that this population of children are difficult to test, or from the observation that they are unable to access standardised test materials. Finding new ways to test these children, as discussed in the previous chapter, will help to build a more complete picture of their skills and difficulties.

5.3 The Research-Practice Gap in Eye-Gaze Technology

Whilst eye-gaze technology is by no means the only access method to have a "gap" between clinical practice and published research evidence, this disparity is particularly clear for this technology due to its relatively recent arrival and the interest shown by families and professionals alike in its potential. Karlsson and colleagues (2018) point out that clinicians

currently lack the necessary evidence to identify potential eye-gaze users and to accurately match technology options with the user to optimize successful implementation (Karlsson et al., 2018). It has also been observed (Fager et al., 2012) that the training and practice requirements for children beginning to use this technology are yet to be documented or fully understood; the bulk of the research into training and practice being carried out in literate adults with acquired neurological conditions such as motor neuron disease.

In a recent systematic review into the effectiveness of eye-gaze control technology for facilitating communication across different social contexts for people with cerebral palsy and significant physical disability (Karlsson et al., 2018), research was found to be sparse, with only two papers with low levels of evidence meeting the criteria for inclusion. One of these (Borgestig et al, 2015) is discussed in more detail below. The authors of the review concluded that "given the potential for eye-gaze control technology to make a substantial impact on the lives of people with significant disability, there is little research to guide assessment for optimal configurations of hardware and software technology, training of users and their communication partners" (Karlsson et al., 2018, p. 7). The authors also highlight that, whilst the technology continues to be provided frequently for children and young people, objective evaluation of the outcomes of such provision is lacking.

It has been observed that, when clinical practice drives the development and use of an intervention without concurrent research, the underlying beliefs and values on which that practice is based may not always be sound, but tend to give rise to a form of confirmation bias (Mirenda, 2017). In the case of eye-gaze, the elevated levels of expectation may lead to clinicians implementing the technology in the hope or belief that exposure to it will result in performance gains. Coupled with the assumptions described above, this can lead clinicians towards a tendency to over-prescribe this technology. Returning to the systematic review by Karlsson and colleagues (2018), a key rationale for the work which follows is found in the authors' conclusions:

[In the eligible studies identified by the review process] an assumption is generally made that people with significant motor disability should be given the opportunity to use an alternative form of communication and that eye-gaze control technology may be the only option available. Trialling this technology is, therefore, a responsible action. Screening procedures to provide direction for clinicians and clients in selecting appropriate systems for trialling would be useful to streamline the phase during which trialling of devices takes place and maximizes the likelihood of a well-suited system being purchased.

(Karlsson et al., 2018, p. 6)

The lack of research into the cognitive, linguistic, social, sensory and motor demands of access technologies including eye-gaze control may lead to the technology being provided to children who are cognitively unable to understand the concepts involved in controlling a computer with their eyes (Light & McNaughton, 2013). This in turn can lead to device abandonment and unnecessary spending for services providing the technology (J. M. Johnson et al., 2006; Karlsson et al., 2018). For parents, it can lead to disappointment or to disputes with clinicians and a breakdown in the therapeutic relationship (Anderson et al., 2016; Bailey, Parette, Stoner, Angell, & Carroll, 2006). For the individual, the incorrect selection of a device or access method can lead to time wasted attempting to learn to use inappropriate technology (Gosnell et al., 2011).

5.3.1 Evidence for Progress and Teaching

For the population of children with cerebral palsy (CP) and other severe motor impairments, existing evidence suggests that, whilst some children may make improvements in their performance on specific tasks, such gains are likely to require long-term investment of time and resources (Anderson et al., 2016; Borgestig et al., 2016; Stokes & Roden, 2017). Borgestig and colleagues (2015), for example, looked at ten non-verbal children with severe physical impairments, none of whom had any previous experience of using eye-gaze technology. These children were all issued with eye-gaze devices and their parents and support team were given a dedicated two-day introduction to the technology and the software they would be using. Thereafter, the technology was used daily, with regular input from a multi-disciplinary team for 9 – 10 months and no other interventions being carried out during this time. Regular planning and review meetings with all stakeholders were conducted. Longitudinal follow-up of these children indicated that they all showed improvements on an activity involving a single target: with children improving in their speed of targeting after 5 months and in their accuracy after 15 – 20 months. Notably, this study involved a task which was chosen for its low cognitive demand and the fact it did not require children to have a high level of language understanding. This study supports the theory that children with severe physical impairments may need a long time to show improvements in eye-gaze performance and that a large amount of input from professionals is likely to be required (Borgestig, Sandqvist, Parsons, Falkmer, & Hemmingsson, 2015).

5.4 The "Midas Touch" Problem and Interaction Errors

In the field of Human Computer Interaction, The Midas Touch problem refers to a phenomenon that occurs when an input modality shares one channel for control and for observation (Tai et al., 2008). Named after King Midas in Greek mythology, who turned everything he touched into gold, the Midas Touch problem in eye-gaze technology refers to the issue inherent in the technology that it cannot distinguish between the user's gaze for collecting visual information and that used for command input. Thus every user fixation may lead to activation, regardless of the user's intention (Kar & Corcoran, 2017). It has been argued that, in the same way that a pointing device or switch is not immune from accidental activation by involuntary movements of the user, so eye-gaze technology is inherently susceptible to over-registering the movement and rest of a user's gaze (Myrden et al., 2014). Similarly, in some cases where children or adults have previously used their eyes as a means of signalling messages (looking up for *yes* and down for *no*, for example), the use of a single the eyes for multiple functions can confuse both the device and the user, resulting in accidental selections and increased frustration.

In some cases, this problem with an access method can even cause abandonment of assistive technology systems. Leung, Brian and Chau (2013) frame the concept as an "interaction error", describing this as the mismatch between user intent and the access technology output (Leung, Brian, & Chau, 2013). Although the case study they describe (a young person using a vocal cord switch became so frustrated with its accidental activations, which were often triggered by non-target speech sounds, that he rejected the use of the technology) focuses on a switch user, the general principles of false positive and false negative interaction errors are applicable to all access methods which have not been properly matched to the individual user. False positive activations refer to activations which occur without a deliberate expression of functional intent by the user and false negative activations to the inaction of the access method despite this expression. Whilst false negative activations may be less common for eye-gaze technology, the risk of false positive activations is conversely much higher, due to the "always on" nature of the access method exacerbating the Midas Touch problem. Put simply, where a user can be "not using" a switch or a pointing device, they cannot be similarly "not using" their gaze.

Several technological solutions have been proposed for tackling the Midas Touch problem in eye-gaze technology, however these all require the user to execute a specific command or

perform a particular action. These include the use of "rest" commands, which temporarily pause the eye-gaze camera while the user gathers information by looking around the array. Such techniques require the user to have already mastered the device, however, and do not address the problem of all gaze data being registered and interpreted by the device during learning. Thus, errors can arise when the system incorrectly interprets user input (Tai et al., 2008) but can also arise when the software interpreting the gaze data provides feedback in response to any registered gaze point within the screen area.

From the point of view of an onlooker the Midas Touch problem, coupled with error-free software (discussed below), can result in even the smallest or most random movements of the eyes seeming to result in large effects such as the creation of animation and sound on the screen. Whilst such activities may play a role in providing exploration and play activities for young children with physical disability, the Midas Touch problem means that there is a risk of all eye movements and their resulting actions being interpreted as purposeful. The next section discusses this in the context of eye-gaze teaching and training software, which may exacerbate these false positive observations.

5.5 Eye-Gaze Training Software

In the absence of robust evidence on which to base clinical decisions, the gap between research and practice has provided a space for manufacturers of eye-gaze systems to create software that purports to assist clinicians in assessing children for this technology. In addition, these software packages often contain tools or programmes designed to "train" new users, or to "teach" and provide "practice" in the skills required to make purposeful use of the technology. To begin with, these were pitched at adult users, likely with acquired disabilities or neurodegenerative conditions, and included eye-gaze accessible versions of popular board games such as Chess and Connect 4. Games such as these assumed that the user had a typical level of cognitive skill and were included in eye-gaze systems not just for their leisure value, but to help users hone the skills needed to use the technology.

More recently, the field has seen the arrival of eye-gaze teaching and training packages aimed at children and young people. These software packages generally take the form of a selection of games or activities arranged in levels, which may focus on the acquisition of a particular component skill. Often a continuum or "learning curve" is placed on these skills, which may run from early sensory interactions with the system, through "error-free"

exploration, all the way up to mastery of AAC software and computer control. For example, an early "error-free" level might include an activity where animation and sound are triggered wherever the user's gaze point is registered on the screen. This might then progress to targeting single items, then to targeting from an array of different items, then introducing the concept of "dwelling" to trigger an item and then on to making choices where there are correct and incorrect options. The implication is that learning one skill will allow a child to progress to the next and that each skill builds on the previous one. As a result, the use of eye-gaze technology is presented as a sequence of component skills which can be acquired individually and sequentially and which, once fully acquired, will offer a child full control of an eye-gaze system and a means by which to access high-tech AAC. The implicit assumption that underpins this is that all children have the basic skills to make use of eye-gaze technology and the software is acting as a way to help them repurpose these skills.

When these training packages are appraised, however, a number of complications become apparent. Firstly, the levels through which they progress do not always seem to follow on naturally from one another. For example, many teaching software packages will begin by focusing on sensory interaction or exploratory play, progressing towards purposeful dwelling, as described below. However, at various points, elements of "choice making" or possibly even "communication" may be introduced, which are pitched as part of the same continuum of learning as the operational skills worked on up until that point. From a task analysis perspective, there is of course no link between developing dwelling skills and being able to make choices: these are clearly very different skills and the placing of them both in the same continuum of learning may be misleading.

Secondly, in some cases there appears to be a lack of definition around the skills that the software is purporting to demonstrate. For example, some early levels offer "attention grabbing" animations, or "blank screen engagement" tasks where the child is presented with a blank screen on which animation is triggered corresponding to the location of the child's gaze point. The accompanying guidance notes will advise that this is evidence of the child's "looking" at the screen whereas in fact it only shows that the eyes are within the range of the camera and oriented towards the device – a key semantic difference. Previous chapters have highlighted the difference between the orientation of gaze and purposeful looking behaviours. However, as elucidated in the Midas Touch problem above, an eye-gaze system is unable to differentiate between these two distinct acts. Therefore, whilst the more

conscious act of "looking" may or may not be taking place, it is not possible to make a judgement of this purely from the x-y co-ordinates provided by an eye-gaze device. This is even more difficult to judge when the screen is blank, with nothing at which a child could reasonably be said to be "looking".

Expanding on this, some software packages will present users with one activity that teaches the concept of dwelling through having the user dwell on any one of several onscreen items which may move or make noise in order to attract and subsequently hold the users' attention. Once the user has looked at the item for the pre-determined dwell time, the item will react with animation and further sound. When this is looked at through the prism of the Midas Touch problem, such an activity presents a paradox: the user looks at the item because it is moving, and the item continues to move because the user is looking at it. In many eye-gaze learning packages, the movement and fixation of gaze is presented as analogous to pointing at an item on a touchscreen. This must be questioned since, with activities such as this presented on an eye-gaze system, there is no way of the child's simply inspecting the item without the software logging a selection. Once again, there is no way for the software to differentiate between "looking to inspect" and "looking to select". As such, it is conceivable that activities such as this, which purport to show cause and effect or purposeful dwelling for selection, may in fact be producing false positive results since they can be completed using directed visual attention or preferential looking, particularly if the target item is the only thing on the screen. All too frequently, activities that purport to show cause and effect do not include any form of distractor or anything else on screen that must be inhibited in favour of the causal item.

Finally, some software packages will give feedback for parents, therapists and teachers in the form of scores. This feedback is provided to help clinicians measure children's progress or, in some cases, to provide guidance about when a child is "ready" to move to another activity or level. Whilst these will sometimes be objective (such as the time to complete an activity or the number of times a target was hit out of a number of total possible hits), some software will produce feedback that is still subject to interpretation.

An example of this is the frequent use of heat maps, which show which areas of the screen registered the most gaze points. Often, this is presented by the software as showing the areas of the screen children "found most interesting" or that they attended to most often.

On the surface, this seems a reasonable assumption. Holmqvist and colleagues (2011, p. 239), though, point out that "heat maps […] look so simple that it is tempting to draw conclusions from them that often cannot and should not be drawn". They point out that the use of heat maps invites inference about areas of the screen which are shown to have increased gaze activity: "The hot spots become confirmatory examples for our first explanation [inviting] post-hoc interpretations that favour the observer's own hopes or favourite theory" (Holmqvist et al., 2011, p. 239). Whilst heat maps can form a useful part of observing children's use of an eye-gaze device, it is risky to rely on them in isolation since they are simply a graphical rendering of the x-y coordinates of a child's gaze points and give no information on timing, calibration accuracy or the amount of support being given to a child. Returning to the example above, a heat map might show a larger number of gaze points at the location of an onscreen item but it would not be possible to determine if this was due to their being interested in it, responding reflexively to the appearance of a novel item, or using their vision to study it. Nevertheless, heat maps are, in the author's clinical experience, frequently used to make the case that children's skills are improving and have been included as part of the justification for funding requests.

Some eye-gaze teaching packages will provide scores for more intangible concepts, such as ascribing a percentage score to "vision skills" or "cognition". These scores are often based on calculations unavailable to those working with the children using the software. This may lead to a perception that children's vision is improving through use of the eye-gaze. Whilst this may be the case, the lack of task analysis means that children may in fact just be improving in their execution of one specific activity and the benefits to their vision more generally may be over-estimated by those supporting them. Equally, children may be improving irrespective of the use of eye-gaze technology.

Over-reliance on the scores generated by eye-gaze teaching packages presents the risk that crucial observation of the child's behaviour and response will be neglected or relegated to a footnote on a funding request. It has been proposed (Sharma et al., 2014, 2008) that a central principle of developmental assessment is to observe not only what a child does, but also how they do it. Taking the example of cause and effect once more, it is hard to attribute an understanding of this concept to a child based purely on the feedback from an eye-gaze device in the form of percentages, heat maps or arbitrarily determined levels within a software package. A risk exists that children most in need of developmental evaluation would

miss out on this because their skills are being reported only in terms of their results on an eye-gaze teaching software package. In assessment paradigms used with children with physical disabilities, where toys may be replaced by robots or virtual environments (Cook et al., 2011; Encarnação et al., 2014), the importance of observing the child's responses remains a key part of determining whether or not the child has demonstrated the skill.

Allied to this, there exists a presumption that skills used in particular activities will be readily translatable into other contexts. This has in turn led to the perception that eye-gaze technology can be used to teach or improve basic vision skills, although it is far from certain whether or not this is the case.

Despite the popularity and proliferation of these software packages, the evidence supporting their claims is sparse and their role in the assessment process is still disputed. It is very likely that these packages will have utility for children who have established cause and effect, but questions remain about whether they could be used to teach or consolidate that skill.

5.6 Potential Challenges in Teaching Eye-Gaze Access

Whilst the use of eye-gaze teaching software is one approach to teaching children this access method, it is not generally used in isolation. It is known that that the teaching of operational competencies needed to make use of an access system require partners with the appropriate knowledge and skills. In a focus group study into the benefits and challenges of AAC use, McNaughton and colleagues (2008) reported that a major theme identified by parents of young children beginning to use such technologies was the need to teach their children how to operate the device (McNaughton et al., 2008). Several parents in this study commented on the steep learning curve that they faced, needing to learn to operate the technology themselves before being able to teach it to their child. Whilst this is the case for all access methods, supporting a child to learn the skills needed to control an eye-gaze system may be complicated by several additional barriers. These are discussed in the following sections.

Interestingly, the outcomes of a recent Delphi study by Karlsson and colleagues (2020) indicated that respondents from a variety of stakeholder groups felt that regular, frequent practice sessions were the best way to learn and teach eye-gaze access (Karlsson et al., 2020, submitted for publication). No consensus was reached on whether the use of specific teaching and training software packages was helpful, however, with respondents preferring

to have skilled professionals guide the learning programme and for practice to be embedded in existing routines and activities, rather than taking place in discrete sessions or activities.

5.6.1 Modelling

One established method of teaching AAC use or the use of an access method is that of "modelling" the skill that is being taught (Kent-Walsh & McNaughton, 2005; Pennington et al., 2004; Sennott, Light, & McNaughton, 2016). The modelling approach involves the person in the teaching role supplementing their spoken instructions either by pointing to items in the child's communication system, showing them how to use their access system or by physically supporting the child to carry out the action themselves. Modelling is considered to be so important in learning to use AAC that Kent-Walsh and colleagues concluded from a meta-analysis that it was one of four fundamental skills that were most effectively used by skilled communication partners supporting young children with communication needs (Kent-Walsh, Binger, & Malani, 2010; Kent-Walsh, Murza, Malani, & Binger, 2015).

Modelling is also an established part of teaching children to use access methods for independent control, play and leisure. For example, when teaching the use of a switch, instructions to "play more music" or "make the toy move" will often be supported at the outset by the person teaching pressing the switch themselves to demonstrate, or guiding the child's hand to the switch to support the activation (Bean, 2011). Any physical support given to the child will be gradually reduced (a process sometimes referred to as "backward chaining") to help the child move towards independent operation and control (Cook et al., 2014). As an example, when learning to use a mechanical switch to activate a toy, the child observes another person pressing the switch to make the toy move, and then experiments with this themselves, with the adult offering some physical support if required at the early stages.

Eye-gaze presents specific challenges to the process of modelling. Other direct access methods such as touchscreens or pointing devices can be demonstrated easily to the child in the early stages of their use, with the person in the teaching role able to offer hand-over-hand support to help consolidate the link between the input device and the onscreen action. With eye-gaze, as has been previously observed, there is no physical contact between the user and the device. Returning to the literature discussed in Chapter 3, research suggests that young children find cause and effect relationships which are not spatially contiguous

(those where there is no physical contact between the action and the effect) harder to learn (Kushnir & Gopnik, 2007). Again, modelling is often a recommended strategy in these cases: an adult may model the use of a remote control, for example, to help make explicit the causal link between pushing the button and activating the TV or toy. However, such a strategy is not available to the adult seeking to provide instruction in the use of eye-gaze technology, since the movements of the eyes are generally too small to be useful in demonstrating how they might be used to interact with the screen.

Furthermore, there is no useful way to physically support a child in directing their gaze towards the screen. Whilst it is sometimes recommended that a child's head is supported during calibration or to help them initially engage with the screen, this is generally to keep them within range of the camera and there is no practical way to physically affect the direction of a child's gaze in the same way that one might place a child's hand onto a switch to demonstrate how it works.

5.6.2 User Feedback and Proprioception

In the discussion in Chapter 2 of this thesis, one of the key components of an access method is the amount and type of feedback it provides (Fager et al., 2012; Griffiths & Addison, 2017; Higginbotham et al., 2007). Most access methods will provide some auditory and haptic feedback via the input device – such as the "click" of a mechanical switch or the physical sensation of "travel" when depressing a keyboard key, alongside the visual feedback of an action or selection on a device's display. These feedback cues that inform the user that the input methods has been activated are considered so important that technology which does not have moving parts to generate auditory and haptic feedback (such as proximity switches or modern touchscreen devices) often offer the option of generating them using built-in speakers or servos (Lee & Zhai, 2009). The action of placing a finger on a touchscreen provides proprioceptive feedback to the user, creating muscle tension and sensory feedback at the point of contact and providing reinforcement that contact has been made.

With eye-gaze access there is no feedback from the input device, and the proprioceptive feedback from the muscles of the ocular-motor system may not be sufficient to provide any useful clues as to the method of control. With this feedback effectively removed from the equation, the user is solely reliant on visual feedback from the display and needs to make the inference that this is being controlled by the movement and rest of their gaze. This is

further complicated for very young children by the fact that all screens they will have previously encountered display moving images, but do not do so in response to their gaze. Making the causal link between the movement of the eyes and the responses on the screen is therefore even more challenging.

5.6.3 Instruction

Considering the challenges of modelling or demonstrating the use of eye-gaze technology, those tasked with teaching children how to use it are left with fewer strategies at their disposal than might be available for other access methods. Where children have difficulties mastering the skills needed to make use of eye-gaze control technology on their own, the most obvious remaining strategy is that of explicit verbal instruction and feedback. Researchers have suggested that, for some children, the use of verbal instruction can support the development of causal links and relationships between actions and outcomes (Bonawitz et al., 2010). In particular, where cause and effect are not contiguously linked, the addition of verbal feedback describing and making explicit what is happening may help to cement the link between the two.

Petersen and colleagues (2000) describe a method used for teaching switch scanning to typically developing children, which involved explicitly describing what was happening and what the researcher was doing; providing a commentary for the children whilst the use of the access method was modelled (Petersen et al., 2000). The instructions included explicit prompts to guide the child's attention to the cursor ("look how it jumps from picture to picture"), guidance about how the activity worked ("to make the computer work we have to press the green button") and statements about what was going to happen and how to complete the activity ("when *clown* turns black, I'm going to press the green button").Whilst it is possible that the use of verbal instruction may be able to support children in learning to use eye-gaze technology, it is likely that there will be differences in how this is administered. Much of the language used here explicitly referenced the behaviour which was being modelled, which would be difficult in eye-gaze, as discussed above.

Of relevance here is the need to be sure that children understand the verbal instructions given to them. Since many of the children being considered for eye-gaze technology are felt to need help in establishing and consolidating cause and effect, it is reasonable to question whether they would be at a level receptively where they can comprehend the prompts and

pointers given by someone seeking to support their use of the device. One possible method of teaching children through verbal instruction – the use of simplified, causal language instruction – is explored in Chapter 9 of this thesis.

5.7 Conclusion

This chapter has summarised some of the challenges facing clinicians tasked with making decisions about how and with whom to implement eye-gaze technology. Clinicians are faced with a lack of strong evidence on which to base their decisions about whether or not to implement this technology and what the likely progress of children might be. Even when the technology is in place, there is a lack of understanding about how children might best be supported to learn the skills needed to operate it purposefully. The work described in this thesis seeks to address some of this uncertainty by looking at way in which children (both typically developing and those with CP) interact with eye-gaze technology and how the potential differences in the key areas of vision and cognition impact on performance. The next chapter looks in more detail at the methodological design choices made to address these aims.

Chapter 6

Methodological Challenges

This chapter discusses some of the key methodological challenges in working with children with a diagnosis of cerebral palsy (CP) and using eye-gaze technology in assessment. The goal of this chapter is to frame each of the methodological challenges and to explain the decisions taken to address each, providing some insight into how the experiments described in the following chapters have been designed.

6.1 Assessment of Children with Cerebral Palsy

Formal and informal assessment of language and cognition in children with CP can seem a challenging process for clinicians. The need to obtain meaningful assessment results needs to be balanced with considerations of a child's motor and sensory impairment, the impact of attention and fatigue, the need to involve parents in a way which will contribute to the assessment outcomes and the need to ensure that all response methods and modes of communication are made available to the child (Gumley et al., 2011). As has been outlined in the previous chapters, it is often argued that the challenges in assessing this population have led to over- or underestimation of language and cognitive impairments in individuals, as well as the under-identification of comorbid conditions such as autism (Christensen et al., 2014) or specific cognitive impairments within the overall population (Kurmaniviute & Stadskleiv, 2017; Stadskleiv, 2020).

The administration of most standardised tests or assessments to children with CP is usually not possible without adaptation. This is because most standardised assessments of language or cognition require good eyesight, good motor control (with at least an ability to isolate a point), the ability to produce speech (at least "yes" and "no"), the ability to respond within certain time constraints or some combination of the above (Kurmaniviute & Stadskleiv, 2017). Several authors have highlighted the need to ensure that tests administered to this population retain their validity and are not, for example, evaluating a child's ability or inability to carry out a motor task rather than assessing the target skills for which the test was designed (see Geytenbeek, Heim, Vermeulen, & Oostrom, 2010). As such, studies of cognitive and language impairment in this population are scarce when compared with

children without motor impairments (Kurmaniciute & Stadskleiv, 2017; Pennington et al., 2004; Stadskleiv, 2020; Stadskleiv et al., 2014).

When conducting research with a population of children with CP, therefore, experimental and assessment methods used must take into account their physical impairments, as well as the possible presence of learning disabilities and the often severe impairment of functional speech and expressive language.

It is known that children in this population can present with impairments of cognition and language and thus it is important that these are assessed to avoid the risks inherent in assuming children's levels. Since several solutions have been proposed to the challenges of assessing language and cognition in children with CP, the following sections document some of these and explain the decisions taken by the author when designing the experimental protocol.

6.1.1 Use of Informal Assessment

It is acknowledged good practice that assessments of language and cognition should include both formal (standardised) assessment and informal (structured, observational) assessment (C. Adams, 2002; Cass, Price, Reilly, Wisbeach, & McConachie, 1999). Informal assessment, by definition, can vary between children and between clinicians, although some attempts to define it do exist in the published literature. Most definitions cite common components of informal assessment, which distinguish it from simple observation. Murray and Coppens, for example, describe the goal of informal assessment as "translating the symptomology displayed by the person with a communication disorder into clinically relevant information" (Murray & Coppens, 2017, p. 67). Where formal assessment sets out a protocol for testing and obtains quantitative results, informal assessment can be thought of as the "other things" a clinician does during a consultation: manipulating the interaction or context to test a specific theory and return qualitative observations. This might include, for example, hiding a favourite toy from a child with autism during a play session to observe the response or asking wh- questions to test if a child understands these concepts. Other definitions highlight that informal assessment is a process of critical thinking (Dietz et al., 2012), used to answer specific questions or to test a hypothesis in a more naturally occurring context. Some authors (Yin Foo et al., 2013) suggest that informal assessment should include careful review of a client's relevant medical information or clinical history in order to inform what questions the

assessment seeks to address. It is sometimes proposed that informal assessment should take place over several sessions and in several contexts, in order to build up a true picture of a person's abilities.

6.1.2 Adaptation of Existing Assessments

It is often suggested (Kurmanaviciute & Stadskleiv, 2017; Yin Foo et al., 2013) that adaptations or accommodations can be made for children whose motor or speech problems preclude the use of verbal responses or the manipulation of objects required by some formal or standardised assessment tools. However, as previously discussed, care must be taken to ensure that these adaptations minimise the impact on the validity of the test.

Table 2 – Categorisation of Assessment Concessions (adapted from Alant & Casey, 2005)

Type of Concession	Examples	Estimated Equivalence to Original Test / Assessment
Modification	• Easier instructions • Content changes which significantly alter the assessment • Use of a different, less challenging task	Low
Adaptation	• Translation to another language • Use of a scribe • Vocabulary adaptations which do not substantially change the content of the assessment (e.g. using "nappy" instead of "diaper")	Medium
Accommodation	• Allowing breaks or granting extra time • Using an alternative response mode • Changing the setting or timing of an assessment	High

Alant and Casey (2005) propose a framework for categorising test or assessment concessions made for children and adolescents with speech, language and communication needs, including those using AAC. The framework proposes three categories of concession: accommodations (logistical or procedural changes in ways that tasks are administered or presented), adaptation (changes made to the content of a test to allow it to be used more flexibly or in a different context) and modification (changes in the content of the assessment) (Alant & Casey, 2005). This is summarised with examples in Table 2.

Of most interest in the context of the present study is the use of alternative response modes in assessment. This is an important consideration for the group of children who are considered for eye-gaze technology, since it has been demonstrated previously that they are likely to be children who would have the most difficulty reliably using finger or fist pointing to indicate choices or make selections.

It is sometimes suggested that directed gaze can be used as a response modality for assessments; asking the child to look at their choice of object or picture. It is worth highlighting here that there are often issues with the use of such "look-choosing", with gaze being more open to interpretation than pointing or verbal responses (Sargent et al., 2013). In some cases, the use of a "blinded spotter" is employed, where an additional tester who cannot see the location of the test items stands behind the person presenting them to the child. This person is then able to report more objectively on where they feel the child is looking.

Quadrant-based language assessments can sometimes be administered using "partner assisted scanning": a process in which the examiner poses the question or provides the prompt and then points to each item in turn, asking the child to indicate their answer using a *yes* or *no* response. This sort of accommodation will require the clinician to be confident that the child can reliably produce a distinct and agreed response to indicate their choice and this should be established before the testing takes place. Kurmanaviciute and Stadskleiv (2017) compared response modalities (gaze pointing, finger pointing, and partner assisted scanning) in a group of typically developing children and children with CP. Their results showed that the use of different response modalities did not impact on the scores of the typically developing children. In children with CP, considerable variation was noted when using finger or gaze pointing. Therefore, despite its longer testing time, the authors concluded that partner assisted scanning was a viable clinical option for assessing children with motor disorders and co-occurring impairments of vison (Kurmanaviciute & Stadskleiv, 2017).

6.1.3 Use of Computer-Based Assessments

The increased availability of computer technology and in particular the increasing ubiquity of touchscreen tablet devices has led to several assessments of language and cognition being

adapted for administration using a computer. The recently released *Clinical Evaluation of Language Fundamentals – 5th Edition* (CELF-5), for example, can be administered in part via the touchscreen of an *iPad* tablet. The use of this technology has clear and obvious advantages for clinicians: reducing the amount of test materials that must be transported, providing instant scoring and calculation of standard scores and age equivalents and using cloud storage to provide more effective comparison of scores across time. However, at the time of writing, the assessment does not include provision for alternative methods of access. For children with CP, such an assessment would act only as a direct replacement for the paper-based version. Indeed, they may be more difficult to access, since touchscreens without adaptations can be less forgiving than paper-based assessments for children who may need to place their hand on a surface and then reposition it to target their answer.

The need for a computer-based assessment that takes into account the additional needs of children with complex physical disabilities has prompted several attempts by researchers and clinicians to create an assessment which allows for the use of alternative access methods. The most well-known of these assessments is the *Computer-Based Instrument for Low Motor Language Testing* (C-BiLLT), developed by Geytenbeek and colleagues (Geytenbeek et al., 2010). Although not currently available in the UK, this assessment can be completed using multiple access methods (touchscreen, pointing device, switches, eye-gaze, voice activation) and requires minimal motor action. It can test a child's understanding of language from single word to sentence level, with test stimuli which have been carefully designed to reflect the objects and life experiences of children with CP – using pictures of children in wheelchairs, for example, and photographs of objects that do not require manipulation. Additionally, the test features two learning modules, which introduce the layout of the screens and the concepts behind the test and to teach the child how to respond to the test items using their access method. The C-BiLLT has been demonstrated to be acceptable and motivating to children, to be useful and valued by clinicians (Geytenbeek et al., 2010) and to have emerging evidence of good validity and reliability (Geytenbeek, Mokkink, Knol, Vermeulen, & Oostrom, 2014). In the UK, the development of the *Computer-Based Accessible Receptive Language Assessment* (CARLA) has provided a way for clinicians to use alternative access methods and a commercially available piece of AAC software (*Mind Express 4* from *Techcess*) to assess children's understanding of language. CARLA also includes a "training" section to allow children to become familiar with using an alternative access

method to select responses. At present, this assessment has not been validated or tested for reliability.

6.1.4 Discussion and Decision

Acknowledging the above, it was decided that the most robust way to obtain measures of language understanding and non-verbal skills for children with CP was through the uses of adapted standardised testing materials. Where children were unable to point accurately, the use of partner assisted scanning was the preferred response modality. In order to ensure that children were able to give accurate responses, familiar adults were asked how the child indicated *yes* / *no*, and this was tested informally in the warm-up play session for each child. For all assessments, at least two observers participated in order to ensure that children's responses were accurately interpreted. The use of gaze as a response modality for children with CP was not used during the experiments described here, since some of the experiments sought to assess children with comparatively poor functional vision abilities.

The use of computer-based assessments was discounted, since the target measures in this study seek to measure performance with alternative access methods. It was therefore decided that, despite the potential to use such assessments to test this population, it would be unreasonable to expect children to use an alternative method of computer access with which they may not be familiar to respond to assessments, when the overall goal of the study was to examine their performance with just such an access method.

The use of purely informal assessment methods was also not selected, since good informal assessment can be a lengthy and involved process. Children recruited to this study were seen for only one or two testing sessions, and so informal assessment and careful record keeping through field notes was used to compliment the adapted assessments and the target measures. Informal assessment and observation was used, for example, to identify a likely starting point on the formal language assessments used with the children with CP, or to test cause and effect understanding in a play-based session.

Therefore, drawing on the framework proposed by Alant and Casey (Table 5-1) and the work of Kurmanaviciute and Stadskleiv, standardised assessments were sought which had either been previously adapted, or could be adapted, for use by children needing to use partner assisted scanning as a response modality.

6.1.5 Selection of Assessments

For assessing receptive language, the Auditory Comprehension subscale of the *Preschool Language Scale – Fourth Edition* (PLS-4UK) (Zimmerman, Pond, & Steiner, 2009) was used to assess all children recruited to this study. This test has an age range from birth to 65 months (5 years 5 months). The PLS4-UK manual includes some guidance for clinicians on possible adaptations which can be made to the test for children with physical disability. These include careful positioning of the test materials relative to the child, giving additional time and providing minimal physical support to manipulate the toys used in some of the play-based items (Zimmerman et al., 2009). The authors of the assessment also suggest that partner assisted scanning techniques can be used to access the picture-based items on the test, which was a crucial factor in the choice of this test. In line with the discussion above, the authors of the test are careful to stress that, for this technique to be used, the child's *yes* and *no* responses must be established to the tester's satisfaction.

The PLS-4UK has also been previously used in peer reviewed studies of children with motor disorders, including CP. Hustad and colleagues (2010), for example, used the test when working with children with CP of 4 years chronological age (*n* = 34, GMFCS levels I – V), observing that they selected this test as it allowed assessment of earlier skills than others, and that adaptations could be readily made to the test for this population. They reported, however, that for children with more severe motor impairment it was not always clear whether failures were due to lack of understanding of the concept being tested or because the item simply could not be adapted sufficiently to accommodate the child's motor limitations (Hustad, Gorton, & Lee, 2010). As a result, the test was modified for use with children with CP by a Speech and Language Therapist highly experienced in working with and assessing this clinical population (Price, 2017). In addition to the adaptations in the PLS-4UK manual detailed above, the decision was taken to only include items which could be scored using pointing or partner assisted scanning, meaning that 14 / 62 items (23%) were removed. These included items where, for example, the child would be required to point to a specific part of a picture. Details of the included items are included in Appendix A-1. Scoring of the test was also modified accordingly, with the child's raw score on the remaining items used to apply the following formula:

$$Adjusted\ Score\ = \frac{Raw\ Score\ (CP\ Items)}{Total\ Possible\ Score\ (CP\ Items)} \times total\ possible\ score\ (All\ Items)$$

This score was then compared with the norm-referenced tables in the PLS4-UK manual and the six-month age bracket into which the score fell was taken. Children's language age was taken as being the median score for that age bracket (Price, 2017). In consultation with clinical colleagues it was felt that this assessment would allow accurate identification of any language difficulties which would potentially exclude children from the experiments. The other subscale of the PLS-4UK, Expressive Language, was not used during this study as it is designed to measure verbal output and relies on the use of voice and speech. It was not felt that using this subscale would be practical or informative for the target population.

Non-verbal cognitive development was assessed using one subscale selected from the *Mullen Scales of Early Learning* (MSEL) (Mullen, 1995). The scale chosen (Visual Reception) reports a child's ability to process non-verbal information using shape recognition, patterns, visual memory and visual sequencing. Taken together, these skills can provide a measure of a child's non-verbal cognition. The skills tested are largely non-reliant on the understanding of language and, with the help of clinical colleagues with experience in testing children with motor disorders, the test materials were adapted for use by children with severe motor disorders. Although most items on this subscale were considered to be adaptable for children with motor disorders, some (5/33, 15%) relied too much on fine-motor manipulation of objects. Since making changes to these items would have required modifying the test (as defined in Table 2), these items were excluded.

As part of the adaptation process of both tests, the skills of a specialist Paediatric Optometrist were sought to review the printed materials from the MSEL and PLS-4UK. It was recommended that the line drawings in the MSEL were enlarged from their original A5 size (148.5 x 210 mm) to A4 (210mm x 297mm). Following the adaptation, the materials were reviewed by the Optometrist in order to determine the minimal visual acuity required to resolve the images. For the MSEL, a Snellen equivalent of 2/60 was reported, meaning that materials were accessible to those categorised as having severe visual impairment. For the PLS-4UK, visual materials were reported to have a minimum visual acuity requirement of 6/38, placing them in the moderate visual impairment range. Since children with CP who have severe visual impairment were excluded from the study (see Chapters 10 and 12), those included can be assumed to have sufficient vision to see the materials included in the assessment.

6.2 Use of Eye-Gaze Technology with Children with Cerebral Palsy

Another key challenge to be considered is the existing body of research around children with CP and their use of eye-gaze technology.

6.2.1 Eye-Gaze and Eye-Tracking Technology

As discussed in Chapter 2, there is a distinction drawn between eye-gaze and eye tracking technology. This distinction is based on what each of the systems can provide: control of a computer or accurate data on eye movements. This study uses both technologies, although focuses mainly on eye-gaze devices. As such, experiments relating to access are carried out using commercially available eye-gaze systems, whilst information on the visual functioning and performance of children with CP was gathered using an eye tracking system (see Chapter 11). The specifics of each system are detailed in the relevant experimental chapter.

6.2.2 Selection of Cameras

The selection of a suitable eye-gaze camera is sometimes a challenge for clinicians, since the range of cameras on the market all offer subtly different features. The clinical rationale for the selection of one camera over another is often based on a clinician's own experience with different types of camera. As has been previously discussed, it is sometimes difficult for these decisions to be made objectively since some data pertinent to the tracking algorithms of cameras is often classed as commercially sensitive. However, one feature that is useful for clinicians, and was also considered for this research project, is the size of the "trackbox" – the area in front of the camera within which it can detect and track a user's eyes. For children with CP who have difficulties maintaining head position, this is particularly advantageous. It is on this basis that the choice of cameras from *Tobii Technology* was made for use in these experiments, having a larger trackbox than comparable cameras on the market at the time.

6.2.3 Eye-Gaze Calibration by Children with Cerebral Palsy

As discussed in Chapter 2, calibration of an eye-gaze or eye tracking device is important to allow reliable control or collection of accurate gaze point data. However evidence suggests that children with a diagnosis of CP may have more difficulty in calibrating typically developing peers or children without a motor impairment (Light & McNaughton, 2014b). Children with CP are at greater risk of a number of issues which may affect calibration. These include physical dysmorphologies of the eye, oculomotor impairments, reduced acuity and

difficulties with visual perception. Difficulties with maintaining attention may also impact on whether a calibration is possible or how one might be carried out (K. Holmqvist et al., 2011; Nyström et al., 2013). In addition, completing a calibration procedure requires that the head is kept within the trackbox of the device and the eyes oriented towards the screen while the procedure is carried out. This may well be difficult for some children with CP.

In Chapter 2, the number of calibration points was discussed, as well as the method of calibration (automatic, user-controlled or operator-controlled). There is some potential utility in using fewer calibration points and an automatic calibration, which would require children to keep their head upright and maintain engagement with the calibration task for a shorter period.

As an extension of this, it is possible to address potential challenges with calibration through the design of test materials. On an eye-gaze system, onscreen items can be sized so that they can be selected using the default calibration. This can be additionally augmented by the use of AAC or computer control technology with features such as "snapping", which aggregates gaze points within a target area to facilitate fixation. This means that, for example, a child is able to fixate on any point (or points) within the target area and the software assists by totalling these fixations until they meet the set time to activate a selection. Some software will also retain progress towards a fixation, retaining the total amount of fixation time in an area if the user's gaze moves outside of it. Typically this time counts downwards at the same rate until it either reaches zero or the user's gaze returns to that area. Additionally, AAC software will often place the user feedback marker at the centre of the item in order to assist with drawing the user's eyes to the middle of any item. This reduces both the accuracy demands placed on the user and reduces the requirement for a high-quality calibration.

6.2.4 Other Challenges

Even when a good and reliable calibration is achieved, there are still many challenges to the use of eye-gaze technology in assessment and intervention. Fatigue and eye strain can play a part in performance with an eye-gaze system and users regularly report that the technology is tiring for them to use, especially in the initial stages when learning (Najafi, Friday, & Robertson, 2008). Many children with a description of CP may also be taking various medications, the side-effects of which might include dilated pupils. Extreme pupillary dilation, which is sometimes caused by muscle relaxant drugs such as Trihexyphenidyl, has

been shown to impact the ability of an eye-gaze device to determine the features of the eye needed for accurate tracking (see Chapter 2). Similarly, some medications may cause latency in eye movements, which may impair performance on some activities.

The impact of seating and positioning, particularly head position, on children's access to a computer is well documented (Costigan & Light, 2010; Griffiths & Addison, 2017), and this is particularly the case for eye-gaze technology where the ability to keep the head within the trackbox of the camera is of critical importance. Good seating position is important to maintenance of head position and control in children with CP and, although eye-gaze control systems will include the ability to recapture the user's eyes if they leave and return to the trackbox area, ideally the user's head should remain within this area whenever possible.

6.2.5 Discussion and Decision

The decision was taken to use eye-gaze control technology for most of the experiments in this thesis. This technology most accurately reflects the types of systems to which children with CP are exposed. Further, it is these systems for which the learning and teaching software applications discussed in the previous chapter are designed and marketed.

Owing to the difficulties that this group of children have with calibration, it was decided that the calibration method would be recorded for each child and that this would form part of the results and discussion for each chapter, as recommended in the published literature (Light & McNaughton, 2014b). For most experiments, a five-point calibration was used since this is the default for the eye-gaze devices selected. A two-point calibration was used as backup. Where possible and practical for the experiments, onscreen items were sized and spaced so that they could be accessed using a default calibration profile. It was considered more important that the children remained engaged with the activities than that a lengthy calibration procedure was conducted.

Where more accurate information about a child's gaze behaviours were required, research-grade eye tracking technology was used. Since this technology requires much more accurate calibration, it was expected that some children would not be able to calibrate, although every effort was made to use a calibration method appropriate to the child. This is described in detail in Chapter 11.

In order to ensure that the impact of fatigue was minimised, all children participating in the experiments were provided with regular breaks and were always accompanied by an adult who knew them well and could identify signs of tiredness. Some children with CP were assessed over multiple sessions in order to ensure that fatigue was managed. Parents were also asked to ensure children with CP were in their most supportive seating and typically developing children were seated on appropriate chairs or on the lap of a parent or familiar adult.

6.3 Use of Typically Developing Children in Disability Research

One key methodological challenge in conducting research in AAC or computer access for children with disabilities is that of subject selection. It is widely recognised that users of AAC are a heterogeneous population (Higginbotham, 1995; Higginbotham & Bedrosian, 1995) and that a broad range of differences exist between individual AAC users with respect to cognitive, linguistic, physical and sensory presentations. Additionally, environmental factors such as differing previous experience with an access method or a child's AAC intervention history may make the identification of a homogeneous-like group difficult for researchers (Bedrosian, 2003). As such, drawing conclusions about any population from a sample of participants is difficult and results are often not generalisable.

Several solutions have been presented to this problem, including the establishment of guidelines for the precise, uniform description of participants in AAC research (Pennington et al., 2007). These guidelines and recommendations foreground the importance of careful description of participants: including their health status, cognitive and communication abilities, but also their environment and communication partners. Such an approach is designed to run contrary to the "patient uniformity myth" (Kiesler, 1995), moving away from the idea that patients with commonalities such as disability, age or gender form a homogeneous group. It remains the case however, that finding enough subjects with similar profiles in order to meaningfully test a specific intervention is challenging. Whilst carefully describing and delineating the participants in a research study is a critical aspect of determining whether an intervention has been successful for a particular group (Sevcik, Romski, & Adamson, 1999), controlling for the many possible confounding variables related to an individual's disability, and the potentially inter-related nature of these, is difficult if not impossible.

With regard to experimental design, it has been suggested that single-subject experimental designs may be a more practical research methodology than group research designs (Bedrosian, 2003), particularly in studies on the efficacy of AAC intervention, due to these difficulties in finding a group that are sufficiently similar to provide meaningful results. However, the use of such designs can potentially reduce the generality of any findings, particularly if no selection criteria are employed by the researchers. In such cases, even the identification of a clinically or statistically significant finding will become difficult to relate to other individuals, particularly if they do not share some or all of the characteristics of the individuals tested (Higginbotham & Bedrosian, 1995).

Another potentially helpful way of identifying subjects for AAC or computer access research is the matching of individuals whose characteristics are relevant to the research question, regardless of their disability status (Higginbotham & Bedrosian, 1995). Only characteristics which have a direct, functional relationship to what is being tested are relevant for consideration. When testing an access method, for example, relevant characteristics might include any previous experience with the method being tested, speed and accuracy with other access methods and the ability to maintain attention to task.

Extending this principle, another proposed solution to the challenge of subject selection is the use of nondisabled participants, who are likely to form a more homogeneous population as confounding factors such as motor, sensory and cognitive impairments are much less likely to be present. Additionally, such subjects are less susceptible to fatigue and will therefore display more consistency, not being prone to fluctuations in performance which can present in the population of people with physical disabilities. It is therefore easier to determine whether any effects observed result from the skills of the participants or from the experimental conditions (Higginbotham, 1995; Wilkinson, O'Neill, & McIlvane, 2014).

In addition to their more homogeneous presentation, conducting research with nondisabled participants has several other, practical advantages. From the perspective of researchers, nondisabled subjects are easier and less expensive to recruit, given the low instance of people requiring AAC or specialist computer access in the general population (Higginbotham, 1995).

The use of nondisabled participants in AAC and computer access research has a long history. Many studies looking at aspects of communication use such as working memory (Wagner & Jackson, 2006), symbolic comprehension (Worah, McNaughton, Light, & Benedek-Wood, 2015), semantic categorisation and selection set design (Wilkinson & Light, 2011). The reason most frequently cited for this is the need to carry out research without the confounding variables associated with many disabilities. Aspects of AAC related to the use of specialist access technologies such as switch scanning (McCarthy et al., 2006), control of a mouse pointer (Costigan, Light, & Newell, 2012) and eye-gaze access (Wilkinson et al., 2014) have frequently been researched in nondisabled participants, with some researchers suggesting that such subjects may be best suited to the early stages of human computer interaction research, since research with nondisabled participants is important to construct performance distributions to which the AAC population can be compared (Higginbotham & Bedrosian, 1995) in order to better understand any differences in performance observed in populations with disabilities.

6.3.1 Discussion and Decision

The overall goal of the study described in this thesis is to assess the eye-gaze access skills of children with CP. However, since this population can be difficult to assess and present many potentially confounding variables, it seemed logical to reduce or remove some of these by developing the experimental materials using typically developing, nondisabled participants. This allowed the development of activities and test materials which were suitable for children with a similar developmental age to the target population, as well as ensuring that challenges such as head control and difficulties with language and cognitive assessment were removed.

6.4 Experimental Design

In the previous chapter, it was discussed that many eye-gaze teaching packages offer training in skills such as cause and effect. However, many of these packages include levels of support and scaffolding that may "over-inflate" children's performance in these skill areas. The challenge for this thesis was to design experiments that were simple and motivating enough to engage developmentally young children, but which would target the skills to be tested.

When designing the initial experiments for this thesis, ideas for cause and effect testing paradigms were sought from the literature. Several studies (Bonawitz et al., 2010; Gopnik,

Sobel, Schulz, & Glymour, 2001; Kushnir & Gopnik, 2007; Sobel & Kirkham, 2006; Yang et al., 2013) were identified and reviewed and common factors pertinent to the design of an eye-gaze assessment were identified.

Firstly, it was important that the tasks included an element of learning, so that children could themselves explore the functioning of the eye-gaze device and of any onscreen items available for selection. Secondly, of clear importance in experimental design was the inclusion of a "distractor" or a "null" item: one which was similar to the causative item which must be inhibited by the child when completing the activity. This would ensure that what was being tested was children's understanding of the causative link between their eye movements and control of the device, as opposed to preferentially looking at the only item present on the screen (see Chapters 2 and 3).

It was also decided to include a dwell selection (where the user needs to look at an item on the screen for a pre-set amount of time in order to make a selection) in the design of the initial experiments, in order to increase confidence that children's selection and triggering of the onscreen items was purposeful and not the result of the eye-gaze device registering their gaze point within the onscreen area of the causative item. A standard dwell selection of 1.0 seconds is usually offered by AAC and other computer control software and this was determined, based on clinical experience, to be a useful length of dwell to use, since it likely allow both typically developing children and those with CP to make selections without risking triggering items by mistake.

The above design decisions also address the Midas Touch problem as described in the previous chapter, since they ensure that there is always a "correct" and "incorrect" selection on the screen and place a requirement on the user to purposefully trigger a selection.

Finally, it was decided that the language component of the experiments should be removed as far as possible, in order to ensure that children's understanding of language would not be a confounding factor on their performance.

6.5 Conclusion

This chapter has explained some of the challenges facing researchers working with children with CP and eye-gaze technology. The justifications for decisions taken to address these

challenges have been explained. This includes the decision to develop the testing materials using a population of typically developing children. The following chapters summarise the first three experimental rounds in this study, looking at refining the design of these testing materials using typically developing participants and conducting preliminary investigations into the way in which these children learn the causal relationships required to make use of eye-gaze technology.

Chapter 7

Examining typically developing pre-schoolers' ability to use eye-gaze technology to play a game

7.1 Introduction

In Chapter 5, the challenges presented to clinicians by eye-gaze teaching and training software are discussed. In particular, this chapter highlighted some the discussion around cause and effect and the claims which are made by some software training packages about being able to demonstrate, teach or consolidate this skill. In Chapter 3, the research summarised indicated that children learn to apply cause and effect to the world around them as a result of imitation, trial and error.

The discussion of access methods, and the highlighted challenges that eye-gaze technology in particular may pose, leads to the question of how cause and effect might present or be acquired differently when applied to eye-gaze control. The work described here provides a baseline of children's intuitive ability to infer the control mechanism and apply it to a simple game. Given the relative paucity of feedback with which to make the link between eye movements and onscreen responses, it is not unreasonable to speculate that there will be different challenges in inferring the causal relationships needed to make use of eye-gaze technology.

The experimental work described in this chapter looks at whether children with established cause and effect understanding can independently apply this knowledge to an eye-gaze control task.

The specific research questions addressed in this chapter of the thesis are:

1. At what developmental age can children apply knowledge of cause and effect to complete a simple game using an eye-gaze device?

2. What is the relationship between developmental age and performance on eye-gaze control in typically developing children?

7.2 Research Design

This chapter investigates the relationship between developmental age and young children's ability to learn and apply cause and effect to an eye-gaze control game. The game is based on an experimental paradigm similar to that used by Yang and colleagues (see Section 3.2.3), where children are first exposed to the properties of an item that results in an action, and one that does not. These are termed the "effective" and "ineffective" conditions, which will be the terminology used in this chapter when describing the experiments. Children are then shown a third "hybrid" condition where both items are present in order to assess whether they have learned and can subsequently apply the required skill (Yang et al., 2013).

The experiment described in this chapter involves observing children's exploration of new and novel stimuli presented on an eye-gaze device and looking at their understanding of the technology without direct or explicit instruction, in order to ascertain whether they could independently and intuitively acquire and apply the cause and effect skills needed to control and use eye-gaze technology.

The research adopted a small-scale, cross-sectional design. In the experimental task, children were required to use the eye-gaze device to select the effective button, which moved a cartoon animal one rung up a six-rung ladder towards an associated food. Another button on the screen which performed no action was included as a distractor to demonstrate whether children could inhibit this in favour of the effective button, and that they were not simply looking to the new item on the screen whenever the target button appeared. The independent variables for the task were the language age equivalent, chronological age and non-verbal age equivalent of the children. The dependent variables were the number of trials which elapsed before each child activated the effective button on 6 consecutive trials, thus completing the task and receiving a reward and the time taken for the child to activate the effective button on each of the six consecutive correct trials.

If children had acquired the knowledge of cause and effect in the context of eye-gaze technology, it would be reasonable to expect that they would choose the effective button preferentially over the ineffective button in the final hybrid condition. Similarly, it would be reasonable to expect that the time taken from presentation of both items to the selection of the effective button would decrease over time, as the child's understanding of the function of this button was repeatedly confirmed and reinforced.

The experimental protocol consisted of background measures of language understanding and of non-verbal age followed by the eye-gaze control activity.

7.3 Methods

The following sections describe the methodology of this first group of experiments, as well as the participants and recruitment strategy.

7.3.1 Participants

30 children (15 male, 15 female) were recruited to this phase of the study, aged between 18 and 47 months (M_{age} = 34.03, SD = 8.22).

7.3.2 Ethical Approval

Ethical approval for this section of the study was granted by University College London Research Ethics Committee (Project ID 1328/006). A copy of the ethical approval is included in Appendix B-1.

7.3.3 Recruitment

All children recruited into this phase of the study were typically developing with no reported disabilities. Children were recruited from a single nursery in Hertfordshire. Copies of the information sheet (see Appendix B-2) were given to management staff at the nursery, who in turn provided them to parents of children under four years of age. Parents who were interested in enrolling their children onto the study were invited to complete the expression of interest form, providing their contact details and agreement to be contacted to further discuss the study. If, after these discussions had taken place, parents still wished their children to be involved, they were provided with a standard consent form (Appendix B-3) to complete, sign and return to the nursery management team. Arrangements to see all children enrolled on the study were made directly with the nursery.

7.3.4 Inclusion Criteria

All children recruited into the study met the core inclusion criteria of having no reported hearing, visual or cognitive impairments, and reported understanding of cause and effect with physical objects.

7.3.5 Participant Characteristics

All children recruited to the study underwent background assessment of their language understanding and non-verbal understanding. These background measures were intended to confirm that all children in the study were indeed developing typically. Language understanding was assessed using items taken from the receptive language sub-tests of the *Pre-School Language Scales – 4th Edition* (PLS-4, Zimmerman, Pond, & Steiner, 2009). Expressive language was not tested as the experimental procedures had no specific expressive language component. Using the procedure described in Section 6.1.5, each child's score was given as an age-equivalent range of six months. Assessment of the children's non-verbal age was made using the Visual Reception sub-test of the *Mullen Scales of Early Learning* (MSEL, Mullen, 1995). Details of the children's chronological ages and language and non-verbal age equivalents are included in Table 3.

7.3.6 Equipment and Testing Environment

All children were tested in a quiet, familiar side-room of the nursery. The experiment was conducted in two or three sessions, depending on each child's attention and fatigue. Each child completed the background measures (PLS-4 and MSEL) in one session and then completed the eye-gaze control experiments during a subsequent session on either the same or the following day.

Children were accompanied into the room by a familiar adult and were seated on a standard classroom chair in front of the testing materials or the eye-gaze device. Where children appeared nervous, they were able to sit on the lap of the familiar adult. In order that the eye-gaze control device did not track the adult's eyes, they were asked to keep their eyes closed during any activity using the eye-gaze control device. The room was laid out with the eye-gaze device on a central table (58cm high), ensuring that sunlight was not shining directly onto the screen, as recommended in the manufacturer's specifications. The eye-gaze device used during the experiments was a *MyTobii P10*, which has a 15" screen (4:3 aspect ratio, 1024 x 768 resolution). Children were positioned according to the best- practice guidelines published in the manufacturer's instructions (Tobii Technology AB, 2006): seated approximately 60cm from the screen with the child's eyeline falling within the top third of the screen. The in-built positioning guide software (shown in Figure 16) was used to

Table 3 - Chronological Age, Language Understanding and Non-Verbal Age Equivalents

Participant ID	Chronological Age (Months)	PLS-4 Language Understanding Age (Months)	MSEL Non-Verbal Age (Months)
P01	35	36 – 41	40
P02	47	42 – 47	45
P03	37	30 – 35	34
P04	20	18 – 23	18
P05	20	18 – 23	18
P06	36	42 – 47	46
P07	46	48 – 53	48
P08	34	36 – 41	40
P09	32	30 – 35	33
P10	40	42 – 47	46
P11	40	36 – 41	40
P12	33	30 – 35	32
P13	45	42 – 47	46
P14	44	42 – 47	43
P15	42	48 – 53	48
P16	36	42 – 47	42
P17	22	18 – 23	22
P18	38	36 – 41	37
P19	37	36 – 41	38
P20	37	36 – 41	38
P21	26	18 – 23	24
P22	35	36 – 41	36
P23	32	30 – 35	34
P24	18	18 – 23	20
P25	39	36 – 41	41
P26	28	36 – 41	35
P27	24	24 – 29	24
P28	22	18 – 23	24
P29	34	36 – 41	36
P30	42	42 – 47	44

check that the child's eyes were within the trackbox of the device and could therefore be tracked by the eye-gaze camera.

For the *MyTobii P10* the trackbox measures 30 x 15 x 20cm (Figure 17). All test stimuli were presented within *Microsoft PowerPoint*, using Windows Control to access the onscreen items.
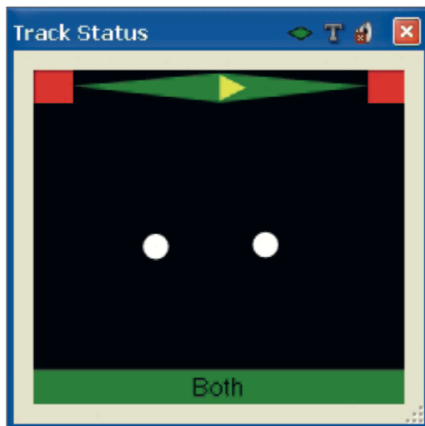
Figure 16 - Screenshot of the MyTobii positioning guide
The yellow triangle shows the distance from the device and the white dots in the centre of the box indicate that the child is optimally positioned.
(Tobii Technology AB, 2006)
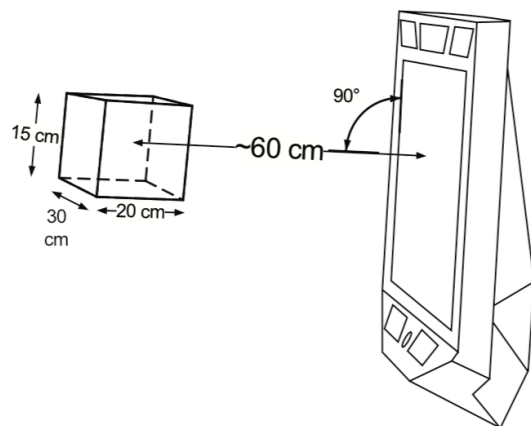
Figure 17 - Graphical representation of the area in which the MyTobii P10 can track a users' eyes
(Tobii Technology AB, 2006)

The screen recording software *Wink* (Kumar, 2010) was used to record onscreen activity and cursor movement for post-hoc coding. In order not to impact on the performance and responsiveness of the eye tracker, screen recordings were taken at 10 frames per second.

7.3.7 Calibration

Before using the eye-gaze control device to take part in the experiments, the device was calibrated for each child to ensure that they would be able to accurately control the onscreen cursor. A five-point calibration was used for all participants, as this is the only setting permitted on the *MyTobii P10* device. Since difficulties with calibration are infrequent in the typically developing population (Light & McNaughton, 2014b), a five-point calibration was considered achievable for all participants. Children were asked to keep their heads as still as possible during the calibration sequence and a continuous, automatic calibration was used, where the software automatically advances to the next calibration point once it has sampled

the required amount of gaze data. At the end of the calibration process, a graphical representation of the quality of the calibration is presented and was reviewed to ensure all points had been calibrated sufficiently well to allow accurate control in all areas of the screen. This graphical representation displays the error vectors recorded by the calibration procedure - lines that indicate the difference between the points of gaze recorded by the eye tracker and the actual location of the calibration point (Dalrymple et al., 2018) and give a graphical representation of the accuracy and precision of the recorded gaze points. Where one or more of the points was noted to have long or widely spaced error vectors, attempts were made to recalibrate these points. However, this was attempted only once per child, in order to ensure that they did not lose interest in the procedures before the learning and hybrid phases.

7.3.8 Experimental Measure of Eye-Control

The experimental tasks used consisted of two learning conditions, exploring the functions of the effective and ineffective buttons, followed by the hybrid condition in which knowledge acquired was applied to complete a game. This is depicted in Figure 18, below.
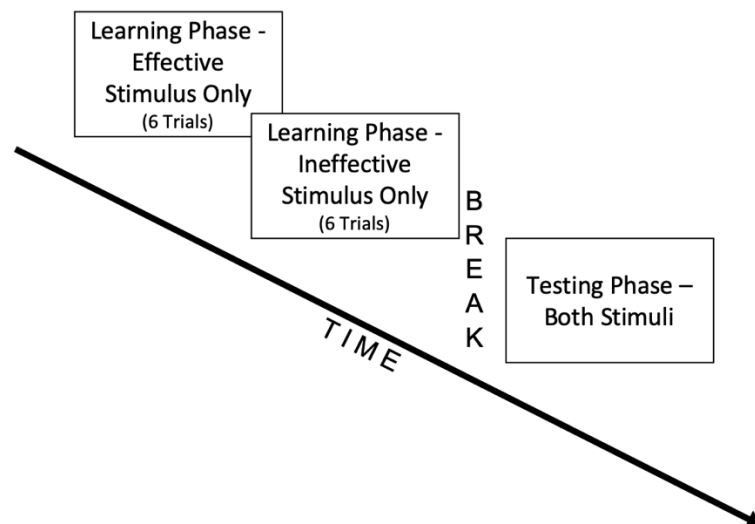
Figure 18 - Schematic representation of the experimental procedure

In keeping with the observations of Yang and colleagues that children had more difficulty generalising causal learning when the stimuli or context were altered (Yang et al., 2013), the basic layout of the screen was the same for all conditions, with a six-rung ladder on the left

side of the screen. At the bottom of the ladder was a cartoon image of an animal (for example a mouse) and at the top was a cartoon image of an associated food (some cheese), as shown in Figure 19.

A "minimal prompting" approach was taken to the provision of instructions to children taking part in the study. This rationale was adopted from a similar study of an access method (switching) by McCarthy and colleagues, who discussed that, since the intent of the study was to investigate the effects of an access method on learning, only minimal instruction was provided for the children during the learning sessions to ensure that they were not given information that might reveal how the device and the activity functioned and invalidate the experiment (McCarthy et al., 2006). Although the current experiment does not explicitly look at comparing access methods, the minimal prompting strategy was considered a helpful one.

Figure 19 - Basic onscreen test environment

As such, children were not told at any point during the experiment that the device was being controlled by their eyes but were informed before using the eye-gaze device that they were "going to play a looking game". During the experiment, children were not given explicit instructions in how to control the device but were verbally encouraged to "look" or to make sure that they had looked at everything on the screen. Successful selections were reinforced with non-specific verbal feedback such as "ooh" and "aah" sounds, together with verbal praise to keep the child engaged in the activity. Visual feedback regarding the location of the child's gaze onscreen was provided by a cursor in the shape of a crosshair. The colour of the cursor was inverted, so that it would show up as white against the black background and remain visible against either the effective or ineffective buttons. When the child fixated on a

particular point on the screen, this would start the completion of the "dwell" selection. This was indicated (as shown in Figure 20) by a red circle completing around the centre of the crosshair in a clockwise direction over the course of 1.0 seconds. When the circle completed, the device would execute a *click* on whatever was at the location of the centre of the crosshair.
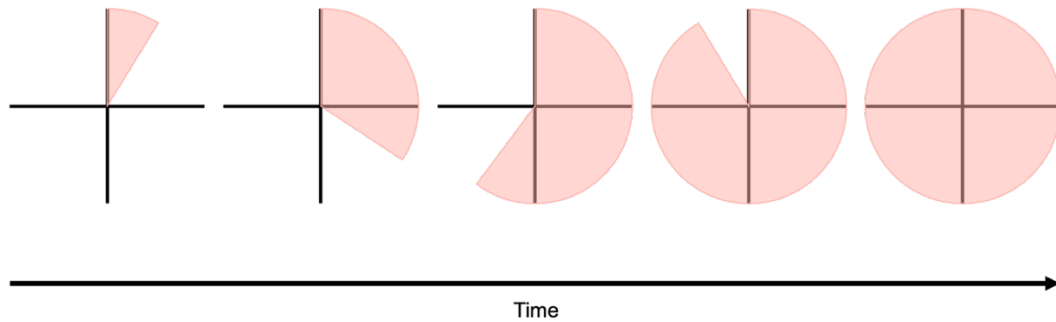
Figure 20 - Graphical representation of the selection marker.
When the child begins to fixate, a circle begins to complete in a clockwise direction around the crosshair cursor. When the circle completes (as shown to the right) a selection is triggered, with feedback provided by a small visual "pulse" emanating from the centre of the crosshair.

7.3.9 Effective Button Learning Phase

The first learning phase consisted of a yellow, circular button (the "effective" button) appearing randomly at one of nine locations on the screen (Figure 21). When the child fixated on the button for the pre-set dwell time, it provided visual and auditory feedback that it had been selected. Auditory feedback was provided in the form of a "ping" sound and visual feedback was provided by a 2.0 second animation during which the button changed colour (cycling through green to blue) and size (pulsating to 1.5 times its original size) before disappearing. After a delay of 0.5 seconds, the cartoon animal "wobbled" to attract the child's attention, before rising vertically one rung up the ladder. This was accompanied by another auditory cue – a rising tone. After a further gap of 2.0 seconds, the effective button appeared again at a different random location. This was repeated six times until the cartoon animal reached the food at the top of the ladder. When the animal had climbed all six rungs to reach the food, a short animation of the animal eating the food played at the top of the ladder. This was accompanied by further auditory feedback in the form of a recording of a crowd cheering and clapping. Verbal praise was also given by the researcher. Children were scored as having passed the effective button learning phase if they had triggered the effective button on all six presentations.

7.3.10 Ineffective Button Learning Phase

The second learning phase consisted of a blue, circular button (the "ineffective" button) appearing randomly at one of nine locations on the screen (Figure 22). When the child fixated on this button for the pre-set dwell time, it disappeared with no visual or auditory feedback. There followed a 5.5 second gap during which nothing happened, with this length of time chosen to match the total time taken by the animations and feedback in the effective button learning phase. After the gap, the button reappeared at another location. If the child did not look at the ineffective button for the pre-set dwell time, it would disappear after a period of 6.0 seconds, leaving the same 5.5 second gap before reappearing in another random location. This was also repeated six times. In order to ensure that children had learned that this ineffective stimulus did nothing, it was recorded when they made an attempt to activate it, so it could be demonstrated that they had seen this.
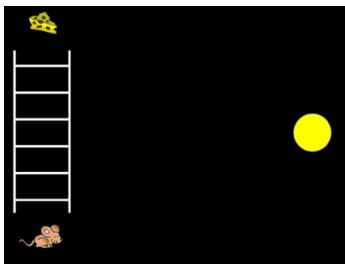
Figure 21 - Sample trial from learning phase with effective button
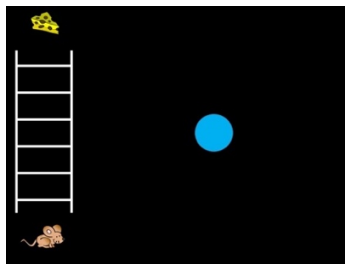
Figure 22 - Sample trial from learning phase with ineffective button
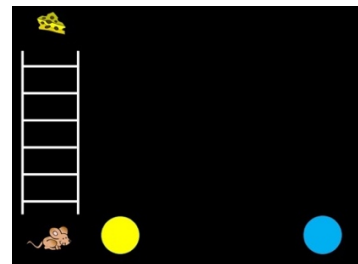
Figure 23 - Sample trial from target phase, showing both effective & ineffective buttons

7.3.11 Hybrid Phase with Effective and Ineffective Buttons

After completion of the two learning phases, the child was immediately presented with the hybrid phase of the experiment. In this phase, both the effective and ineffective buttons were presented on the screen (Figure 23). This phase was designed to assess whether the child had correctly learned the functions of the two buttons and tested whether they were able to correctly select which one would advance the game. In this phase, selecting the effective button caused the same outcome as described in 7.3.9. Selecting the ineffective button produced no outcome but both buttons disappeared for a short period (3.0 seconds) before reappearing in the same locations. The position of the animal on the ladder was unaffected by choosing the ineffective button.

The hybrid phase included a maximum of six variations of the cartoon animal and food pairings (Figure 24), each requiring six activations of the effective button to complete.

Children continued to move through the variations until they had successfully activated the effective button on six consecutive occasions, with no selections of the ineffective button in between. It should be noted that variations in stimuli were included solely to keep children engaged with the task and had no other relevance to the task or scoring. Once children had selected the effective button on six consecutive occasions, they were told that they could stop whenever they wanted to, allowing them to continue to the end of whichever variation of the task they were playing. Again, it is important to state that the scoring was continuous across animal and food pairings so that a child could achieve six consecutive activations of the effective button by, for example, selecting the final three of the mouse and cheese and the first three of the bird and worm variations. When the children indicated that they wanted to stop they were given verbal praise, a small gift (a sticker) and allowed to leave the testing room.
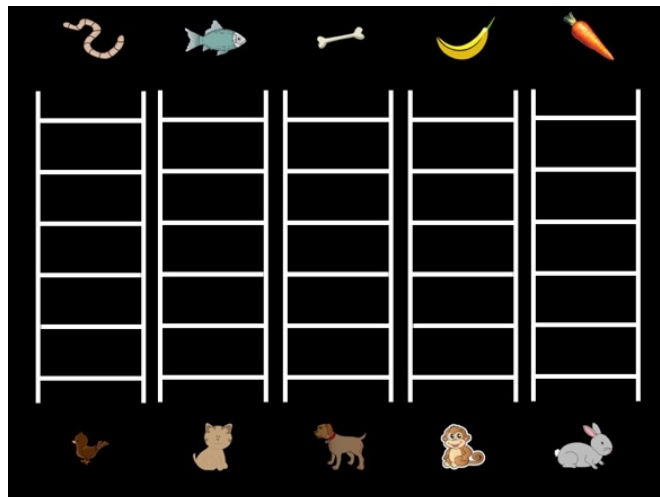
Figure 24 - Other animal and food pairings used in target phase. Including (l-r) bird and worm; cat and fish; dog and bone; monkey and banana; rabbit and carrot

7.3.12 Scoring

Children were deemed to have completed the activity successfully when they had made six consecutive selections of the effective stimulus. This level of successful activation of the effective target was considered to represent understanding of how to control the device; since it represents performance above chance, and allowed for comparison performance between children, even though they may have completed different numbers of trials.

Performance was scored both live during the sessions and subsequently from the screen recordings. For live scoring, a score sheet was developed to allow the researcher to quickly

record the outcome of each trial (selection of the effective or ineffective button). These scorings were checked subsequently against the screen recordings and found to correlate exactly, indicating that this online scoring method was valid for identifying the outcome of trials and the number of trials taken. The score sheet also included space for "field notes", where the researcher could record qualitative observations of a child's behaviour or performance, as well as any other relevant information.

7.3.13 Timing

Following the completion of the experiments, the screen recordings were reviewed in order to collect data on the time that children had taken to complete the tasks. This process involved reviewing the screen recordings and using the timestamps provided by video playback software to provide data on the time that children had taken to orientate to the effective button. An orientation was defined as the time between the onset of the stimulus and the beginning of a dwell within the stimulus area which ultimately activated it. The length of time in seconds (rounded to one decimal place) for each selection of the effective button was thus obtained. This method of recording time data was chosen as it is straightforward and easy to implement and data generated using this method meets the needs of the study, providing an indication of the time taken. Since the data was not generated using accurate tracking software, however, it would not be possible to compare it with similar studies in the field of eye tracking study.

7.3.14 Analysis

The quantitative data collected during the study was analysed using IBM SPSS statistical analysis software (v 25.0.0). Correlational analysis was used to test whether the child characteristic of chronological age and the developmental age measures of language and non-verbal age equivalent correlated with the dependent variables: the number of trials required to activate the effective button on six consecutive occasions and the time taken for each of these final six activations.

All data was first analysed using box plots to identify any outliers (scores of above or below three standard deviations from the overall mean). Tests of normal distribution were then carried out on all data collected. Since all variables were continuous, and the number of participants less than 50, the Shapiro-Wilk test was used to determine this, and to determine whether parametric or non-parametric tests should be used to analyse the strength of the

above relationships. If the Shapiro-Wilk test indicated a significant result ($p < 0.05$) then the non-parametric Spearman's Rank Correlation was used for subsequent analysis. If the same test indicated a non-significant result ($p > 0.05$) then the parametric Pearson's Correlation Coefficient was used.

7.4 Results

The qualitative observations made during the study and the results from the above analysis are presented below.

7.4.1 Calibration

Of the 30 children recruited to the study, 2 (6.67%) were not able to calibrate the eye-gaze device using the five-point calibration. These children were chronologically aged 34 and 37 months, therefore above the overall mean age of the children involved and nothing in the field notes suggested that they were in any way different from the rest of the group. Their language age equivalent and non-verbal cognitive age equivalent scores were in line with their chronological age.

The overall calibration rate for the group (93.33%) is similar to other calibration rates for typically developing children reported elsewhere in the literature (Light & McNaughton, 2014b). The children who were not able to calibrate were allowed to attempt the experimental tasks, but their data was discounted from analysis.

7.4.2 Attrition

Five children (16.67%) were able to calibrate the device successfully but were not able or willing to complete any part of the learning or testing phases, therefore not engaging with the task at all. Reasons recorded for this included being distracted by other people or things in the environment ($n = 2$), refusing to engage ($n = 1$), or persistently preferring to touch the screen ($n = 2$).

A further two children were able to calibrate and to complete both the learning phases (12 trials) but did not engage with the hybrid phase. In both of these cases, these children appeared not to be able to sustain engagement with the task and, despite the researcher's attempts to refocus them to using the eye-gaze control system, they did not re-engage with the task. Looking at the profiles of the seven children excluded from analysis at this stage it

was noted that, at age 18 – 26 months, they are the seven youngest children recruited to the study (M_{age} = 21.71, SD = 2.69). Of this younger group, only two children (those that completed the learning phases) showed any level of engagement with the activity.

7.4.3 Relationship between chronological age, language age and non-verbal cognition

It was expected that there would be a close correlation between chronological age, language age and non-verbal cognition age, since all children included in this experiment were reported to be developing typically. The PLS-4UK provides language age equivalent scores as a range (Table 4), and therefore the midpoint of each range was used for all calculations.

All participants completing the test (n = 21) were included in this analysis. The Shapiro-Wilk's test of normality revealed that chronological age (p = .889), and non-verbal cognition (p = .422) were normally distributed, but language age was not was not (p = .016), although these data approached a normal distribution.

There was a linear relationship between chronological age, language age and non-verbal cognitive age, as assessed by matrix scatterplots. There were no outliers as assessed by boxplots and Mahalanobis Distance. Spearman's correlation was run to assess the relationship between chronological age (M_{age} = 38.00, SD = 5.06), language age equivalent (M_{lang} = 41.29, SD = 5.19) and non-verbal cognitive age equivalent (M_{cog} = 40.57, SD = 4.96).

A strong, statistically significant relationship was observed between chronological age and language age equivalent (r = .772, p < .001) and between chronological age and non-verbal cognition (r = .793, p < .001). A strong, statistically significant linear relationship was also observed between language age equivalent and non-verbal cognition (r = .924, p < .001). Given the strong association between these measures, language age only was used in subsequent analyses. This was primarily because later anticipated examinations of the performance of children with cerebral palsy on similar eye-control tasks would characterise that population using language age.

Table 4 - Results Summary Table for Children Taking Part in Experimental Measures (all times in seconds)

Participant ID	Chronological Age (Months)	PLS-4 Language Understanding Age (Months)*	MSEL Non-Verbal Age (Months)	Number of Trials**	Time to complete each of the final six trials (seconds)						Mean Orientation Time (seconds)†
					Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	
P09	32	32.5	33	20	12.7	13	7.1	7.4	4	1.8	7.7
P12	33	32.5	32	25	3.2	9.1	6.6	12.6	5.1	3.3	6.7
P23	32	32.5	34	27	0.5	9.7	15	5.2	8.9	6.9	7.7
P01	35	38.5	40	14	19.7	20.6	43.5	30.8	2	1.8	19.7
P08	34	38.5	40	12	5.2	4.2	0.9	15.2	3.8	1.2	5.1
P11	40	38.5	40	18	20.2	13	3.9	0.6	4.6	1.3	7.3
P18	38	38.5	37	27	4	19.1	10	1.8	1.1	4.7	6.8
P19	37	38.5	38	21	5	36.2	5.5	8.7	7.2	9.2	12.0
P20	37	38.5	38	18	2.6	3	1.4	1.7	2.1	4.1	2.5
P22	35	38.5	36	19	3.1	3.3	5.6	12.1	29.6	0.6	9.1
P25	39	38.5	41	22	3.8	11.1	22.6	3.9	6.6	16.3	10.7
P26	28	38.5	35	16	1.6	13.2	0.9	14.1	5.9	2.4	6.4
P02	47	44.5	45	17	1.2	10.9	12.5	4.8	8.1	4	6.9
P16	36	44.5	46	17	2.3	20.2	11.9	7.2	5	6	8.8
P10	40	44.5	46	6	20.7	104.6	124.3	110.6	14.8	9.5	64.1
P13	45	44.5	46	7	2.9	54.3	114.5	31	12.2	19.7	39.1
P14	44	44.5	43	21	2.4	45.3	31.5	49.1	22.2	9.2	26.6
P06	36	44.5	42	15	16.2	12.7	2	6.7	8.6	1.3	7.9
P30	42	44.5	44	18	5.7	5.4	10.2	9.8	4.7	17.1	8.8
P07	46	50.5	48	6	6.5	2.2	0.8	3.2	6.1	4	3.8
P15	42	50.5	48	7	27.4	63.5	8.4	10.5	34.9	17.6	27.1

* Figure represents the midpoint of the age equivalent range, see Section 7.8.3

** The number of trials required to activate the effective stimulus on six consecutive occasions, see Section 7.8.4

† The mean of the final six trials for each child, see Section 7.8.5

7.4.4 Relationship between language age and number of trials required to complete the activity

The number of trials required by each child to select the effective button six times consecutively was recorded. The relationship between children's language age equivalent and number of trials to complete the activity was examined.

Language age (M_{age} = 38.00, SD = 5.06) in this group was not normally distributed, although number of trials (M_{trials} = 16.81, SD = 6.39) was normally distributed (p = .178). A Spearman's rank correlation was therefore used. All participants completing the procedure (n = 21) were included in this analysis. There was a linear relationship between number of trials and language age, as assessed by scatter plots. There were no outliers as assessed by boxplots and Mahalanobis Distance. Bivariate Spearman's correlation established that there was significant relationship between language age and the number of trials taken to complete the task (r = -.668, p = .001).

It is interesting to note that all but one of these children are aged above 32 months, with the one younger than that (P12, 28 months) having language and non-verbal age equivalents well above this level.

7.4.5 Relationship between language age and mean orientation time

The time taken for each child to orientate to the effective button on all trials was recorded using the process described in Section 7.6.5. The mean orientation time (MOT) was then generated for the final six selections of the effective button made by each child. On review of boxplots, one outlier was removed from the analysis as the MOT fell more than three standard deviations from the group mean. No further outliers were found on assessment by Mahalanobis Distance.

MOT (M_{MOT} = 11.54, SD = 9.33) was found to be not normally distributed as assessed by Shapiro-Wilk's test (p = < .05). Spearman's rank correlation was therefore used and identified no significant correlation between language age and MOT (r = .282, p = .215).

7.4.6 Change in orientation time across six consecutive successful trials

This calculation was used to determine whether children's speed in selecting the effective stimulus increased over the six consecutive that successfully completed the task.
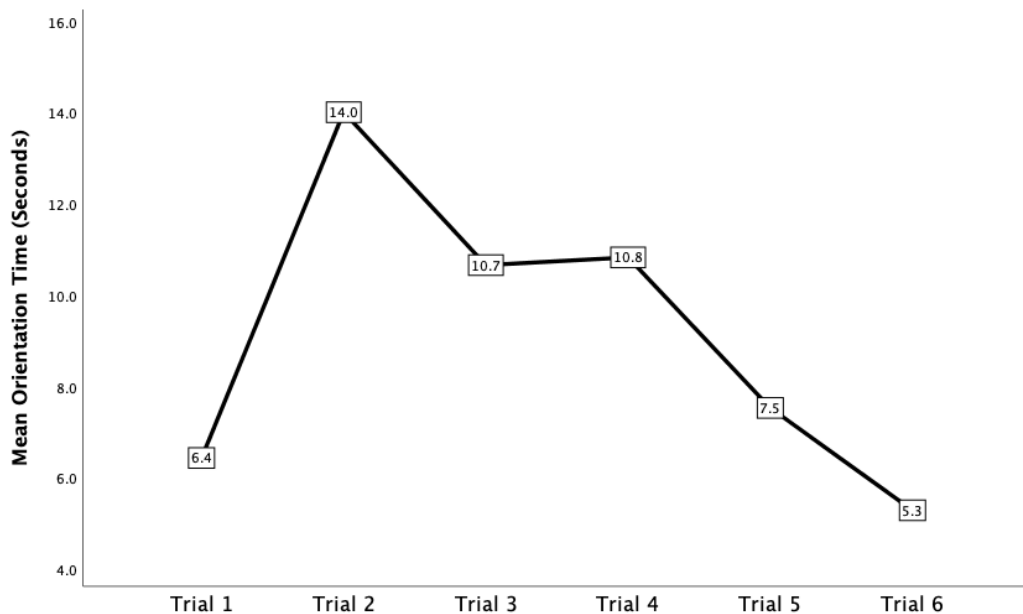
Figure 25 – Graph showing the mean orientation time for all children (n = 18) across their final six trials selecting the effective button.

Means were generated for each of the six consecutive trials on which children selected the effective button, thus completing the activity. Outliers were then identified and removed if they had any one of the six time points that deviated from the mean by more than two standard deviations. In total, three outliers were excluded. The resulting means for each trial were plotted on a graph (Figure 25) for analysis. Figure 25 shows a sloping trend (times getting faster) from trial 2 (5th from last trial) to trial 6 (the last trial), which hints perhaps at some form of increased efficiency in the task, however, the marked slowing in speed of activation of the effective target between trial 1 (6th from last trail) and trial 2 (5th from last trial) mitigates this.

7.5 Discussion

This chapter reports on the first attempt to design experiments to test the requirements for making purposeful use of an eye-gaze device and to address the following questions:

1. At what developmental age can children apply knowledge of cause and effect to complete a simple game using an eye-gaze device?

2. What is the relationship between developmental age and performance on eye-gaze control in typically developing children?

Looking initially at the children excluded from the analysis, it is notable that the children who calibrated but did not complete the task were chronologically the five youngest children recruited. Since these children did engage with the background measures, it is further possible to say, on review of the fieldnotes, that no child with a non-verbal cognitive age or language age equivalent of 24 months or below was able to engage with the eye-gaze tasks for long enough to learn the mechanisms by which the system or the game worked.

Of particular interest here are the two children whose non-verbal cognitive age was reported as 24 months, who calibrated and subsequently passed both the effective and ineffective learning phases of the experiment, but could not complete the final, hybrid phase. On review of the field notes, these children seemed to have been able to infer the causative nature of the effective and ineffective buttons, having completed both learning phases, but were unable to use this information to differentiate between the effective and ineffective buttons in the new context of the hybrid phase. Such an observation is notable when compared with others made elsewhere in the literature, where typically developing children at 19 months of age have been shown to be able to determine causal relationships in toys, but to have difficulties in generalising this knowledge, even when the triggers are the same (Sobel & Kirkham, 2006). What is interesting here is that 24 month old children in a similar study were better able to do this, with performance comparable to three and four year olds (Gopnik et al., 2004, 2001), however the two children in the current study did not seem able to do so.

Two children attempted to touch the screen of the computer during the tasks. Two possible reasons are presented for this. Firstly, children within the age bracket are more likely to be familiar with touchscreens. Secondly, touchscreens present a more obvious causal link between activation and action, meaning children are more likely to choose this method of interacting with them, even after they have been told that they are going to play "a looking game". Indeed, several studies have shown that young children have a preference bias

towards cause and effect relationships which are spatially contiguous than for those which are remote (Bonawitz et al., 2010; Kushnir & Gopnik, 2007).

All children with language and non-verbal cognitive age equivalents above 32 months were able to successfully complete the task. This finding is similar to the existing literature on applied cause and effect, since research cited previously (Bonawitz et al., 2010; Saxe & Carey, 2006; Schlottmann, 2001) has suggested that developmentally younger children do not tend to transfer their observances of cause and effect into action until at least two years of age, unless there is a very clear agent or they are given direction. Neither of these were present in the eye-gaze tasks described here.

In the group of children who did complete the task, a significant negative relationship was seen between language age and number of trials to complete the task, with developmentally older children taking fewer trials to completion.

Taken together, these results suggest that the answer to the research questions is that children are able to apply cause and effect to an eye-gaze system at a developmental level of 32 months, with increases in performance being seen as developmental age increases. This suggests that there may be a lower boundary at which children are able to acquire and apply knowledge of the causative mechanism by which eye-gaze functions but that above that level performance gains fall in line with development, as would be expected for children mastering a novel activity. However, these findings should be interpreted with caution, due to the comparatively small number of children involved in the study and the fact that the correlation between age and performance was only approaching significance.

The results generated by an analysis of the time taken to activate the button also merit discussion. There was not any overall increase in speed across the six consecutive selections of the effective buttons which constituted the completion of this experiment for each child. Whilst it was observed that children with a higher language age required fewer attempts to complete the task, a similar pattern of these children being quicker to complete each attempt was not seen in the data. This raises the question of whether mean orientation time is a useful metric to use in such experiments. Similar cause and effect studies with physical objects do not report time taken to activate the causal triggers, although some report the

amount of time that children spend attending to the causal and non-causal items. The experimental design chosen here would not allow for the collection of such data - the causal item vanishes as it triggers the effect, so children are not able to continue to interact with it. Further, all children in the experiment were encountering eye-gaze technology for the first time so it is possible that, even after the learning phases, there would still be a degree of exploration involved in their use of the device. Challenges in interacting with this new technology, such as the need to sit still and maintain head position within the trackbox of the eye-gaze camera, may also be factors influencing outcomes. Since it was important to the experimental protocol that children were not told they were controlling the device with their eyes, the need to focus and refocus their attention to the task may have contributed to the fluctuating orientation times recorded in this study. As such it is proposed that, in these experiments, the use of timings is a less useful measure of performance than the number of activations needed for children to complete the task.

7.6 Implications for Future Work

Whilst this experiment has provided some insight into the developmental requirements to make intuitive use of eye-gaze technology, it has also highlighted some changes that could be made to the methodology, in order to investigate whether developmentally younger children would be able to engage in the activities.

Of most immediate interest is the observation that children of a lower developmental level seemed to have difficulties engaging with the task for long enough to learn or apply the cause and effect skills required to complete it. The design of the stimuli and the relationship between stimuli and reward are areas that require reappraisal. Making the targets larger and more visually salient would help to engage children better, drawing attention in a way that static shapes such as circles may not. Larger targets would also reduce the requirements for accuracy which, whilst it did not appear to be prohibitive to typically developing children's use of the experiments, might present challenges to children with cerebral palsy.

Further, making the reward more visually exciting and more obviously "tied" to the stimuli (as opposed to being located in another area of the screen) would offer a clearer causal relationship between the stimulus and the reward. As with the stimuli, a more visually

exciting reward is likely to keep children better engaged with the task and is therefore in turn likely to motivate them to continue exploring the causal relationships.

In addition to this, whilst the reward of the animal ascending the ladder was temporally contiguous with the activation of the effective button, it is possible that the spatial dislocation between cause and effect would affect children's learning the causal nature of the link between the two. The experimental design used in this chapter assumed that children would be able to infer this relationship from the observation that both the stimuli and the reward were presented on the same device. However, it is possible that their dislocation to different parts of the screen could have impacted on learning, particularly as this was a completely new technology to all children, and no information on its functioning or operation was provided. Increasing the spatial contiguity between the trigger and the reward may be one way to potentially increase engagement with the task and motivate younger children to explore the relationships between the two.

Finally, having designed this experiment to have an element of sequencing and a clear goal (making the animal climb the ladder in order to get to the food), it may be that this is less important than providing children with a clear and obvious link between their selection of the effective stimulus and the reward. In fact, the presence of other items (the animal, the food and the ladder) on the screen throughout the experiment may have been distracting. It was observed in the field notes that children who attempted to touch the screen frequently attempted to touch the animal in addition to the effective or ineffective buttons, and review of the screen recordings provided evidence that children spent time looking at these other items and even, on occasion, attempting to activate them. It would therefore seem a logical development of this experimental design that the stimuli should be presented against a blank background, with no other items on the screen requiring inhibition to focus on the causal or non-causal items.

7.7 Conclusion

The experiments designed in this chapter have provided initial insight into the developmental requirements of making intuitive use of eye-gaze technology. An ability to infer the causal link between onscreen items appears to be largely absent at 24 months, but to be present by 32 months. A relationship was also observed between developmental age (represented by

language age) and number of trials required to complete the task. These findings, whilst they should be interpreted with caution and are not automatically applicable to a clinical population, are important since some children with CP who are considered for the provision of eye-gaze technology and who are exposed to teaching and learning packages will have developmental ages below this level. The next chapter revises the experimental design in order to examine whether it is possible to engage developmentally younger children with a similar task.

Chapter 8

Reducing the developmental level required to engage with eye-gaze activities

8.1 Introduction

As outlined in the previous chapter, typically developing children with a developmental age of 32 months and above appeared to be able to infer the causal relationships required to control eye-gaze technology. However, a number of developmentally younger children appeared to have difficulties sustaining engagement with the activities used. It is possible that the design of the tasks used in the previous chapter (small targets of a single colour with the reward situated in a different part of the screen) may underestimate the performance of some children, particularly those younger children who had difficulties sustaining engagement for long enough to explore and learn the causal relationships. This second experimental chapter looks at changes to the task that may increase the engagement of children recruited to the study.

As previously discussed, this will be particularly important in the overall context of this thesis, since many children with cerebral palsy have comorbid deficits in attentional control (Bøttcher, Flachs, & Uldall, 2010) which may result in similarly reduced engagement with activities presented on an eye-gaze system. Since many of these children will also have a developmental level lower than 32 months, it is important to test whether the developmental level required to engage with the task can be reduced, whilst maintaining the focus on the establishment of causal relationships. Simply put, this chapter investigates whether more, younger children could engage with the task.

In this task and in those which follow, a distinction is made between children's engagement and their performance. the term "engagement" is defined as being when a child looks at the screen throughout a trial. This may or may not include making a selection. The term "performance" is used to refer to how often a child performs the correct action, selecting the effective stimulus.

8.2 Experimental Design and Design Changes

This chapter uses a similar experimental design to the previous chapter, employing a cause and effect game where children were required to use an eye-gaze device to select a target button and trigger a reward. A small-scale, cross-sectional approach with crossover design was adopted in order to investigate whether the developmental age required to engage with the game could be reduced by changing the nature of the stimuli and the reward.

Although the experimental protocol was similar to that used in the previous chapter, changes were made to the design of the game itself. These changes were based on the redesigned method of switch scanning presented by McCarthy and colleagues in their paper which is further discussed in Chapter 2. This experiment takes the feedback design of this paper, whose authors noted that scanning computer access "does not provide explicit feedback after activation […] to select the target item" (McCarthy et al., 2006, p. 296). The authors therefore designed a feedback method whereby the selected item was animated and moved to a more prominent location at the centre of the screen, with sound accompanying this. It was hypothesised that this method of foregrounding the selected item would highlight more explicitly the relationship between the onscreen cursor, the items and the access method. The reward for activating the effective stimulus was therefore redesigned so that the stimulus did not vanish but instead performed a dramatic animation at the point of selection, then moved into the centre of the screen to be replaced immediately by a full-screen video with bright colours and music. The video was broken into segments, requiring the child to trigger the correct button each time to trigger the next segment and to finally complete the video.

A further redesign focused on the choice of stimuli. Since numerous studies have shown that infants at all stages of development attend preferentially to faces or face-like stimuli (Chawarska, Volkmar, & Klin, 2010; Farroni et al., 2005; Gliga, Elsabbagh, Andravizou, & Johnson, 2009; Schietecatte, Roeyers, & Warreyn, 2012), it was decided that anthropomorphic characters with bold facial features (eyes, mouth etc.) should be used as stimuli. Knowing that moving objects attract attention and hold children's attention for longer (Courage, Reynolds, & Richards, 2006; Richards, Reynolds, & Courage, 2010), the buttons used previously were therefore replaced with highly visually salient, animated characters. The redesign of the stimulus presentation also brought the design of the

experiment closer to that of many eye-gaze teaching packages, where highly visually salient items are presented against a blank background. In contrast to these activities, however, it was ensured that the hybrid measure presented both the effective stimuli and the ineffective stimuli which must be inhibited in order to successfully complete the task. This ensured that the task could not be completed using only preferential looking.

Once again, the experiment consisted of two initial learning phases, during which the children were introduced to each animated character separately and allowed to explore the functions of each. This was followed by the hybrid phase, in which both buttons were presented simultaneously and the children's ability to understand and apply their acquired knowledge of the functions of each was assessed. For children who completed the hybrid phase, an additional phase was presented to see if the skills learned could be generalised to similar, less visually salient stimuli.

To further investigate the impact of these redesigned elements on children's engagement, the way in which the experiments were scored was also reconfigured (see Section 8.4.14). The new scoring system recorded how many presentations of the experimental task each child engaged with, as well as the number in which they activated the effective stimulus. This would also permit further investigation of whether a learning effect took place across the task. It is hypothesised that, as children progress further through the activity, the number of children selecting the effective button on each trial would increase.

Given the findings of the previous chapter that language and non-verbal age equivalents were significantly correlated, it was decided to test only language age equivalent for participants recruited to this phase of the study. This reduced the length of testing sessions. The dependent variables were the number of trials that each participant completed and the number of the times each participant triggered the effective stimulus as opposed to the ineffective one.

For children who were able to successfully complete all phases of the experiment, an extension task was offered at the end of the session. This task investigated whether children could extend the skills learned in the tasks with the visually salient stimuli into a similar task

with static pictures, drawn from a standard graphic symbol library used in augmentative and alternative communication (AAC) systems.

8.3 Research Questions

This chapter addresses the following research questions:

1. Do the changes made to the experimental design allow more, younger children (below 32 months) to engage with the task?

2. Does a learning effect exist as children become more familiar with the properties of the stimuli presented?

3. Can children who demonstrate sufficient engagement and sufficiently well-developed cause and effect skills to complete a game with highly motivating stimuli generalise these skills to similar, less "exciting" stimuli?

8.4 Methods

The following sections describe the methodology of this first group of experiments, as well as the participants and recruitment strategy.

8.4.1 Participants

This phase of the study recruited 32 typically developing children (18 male, 14 female) aged between 11 and 35 months (M_{age} = 29.00, SD = 7.24).

8.4.2 Recruitment

All children recruited into this phase of the study were typically developing with no reported disabilities. Children were recruited from one nursery and two pre-schools in Cambridgeshire, East of England. The managers of each centre agreed to take part in the research and supplied the parents of all children within the target age group (9 to 36 months) with copies of the information sheet (Appendix C-2) and an opt-out consent form (Appendix C-3). Parents were told that they may withdraw their children from the study at any point. All children whose parents did not complete an opt-out form and who gave assent to take part when asked were included in the study.

8.4.3 Ethical Approval

Ethical approval for this section of the study was granted by University College London Research Ethics Committee (Reference 1328/006), detailing the changes to the experiment design outlined above. A copy of the ethics committee application is included in Appendix B-1.

8.4.4 Inclusion Criteria

All children recruited into the study met the core inclusion criteria of having no reported hearing, visual or cognitive impairments. All children had reported understanding of cause and effect with physical objects.

8.4.5 Background Measures

All children recruited underwent background assessment of their language understanding using the same receptive sub-tests of the *Pre-School Language Scales – 4th Edition* (PLS, Zimmerman, Pond, & Steiner, 2009) as used in the previous chapter. Details of the children's ages and levels of language understanding are reported in Table 5.

8.4.6 Equipment and Testing Environment

All children were tested in a separate, familiar room in their nursery or pre-school. Distractions in the room were minimised by covering toys and other items with blankets and ensuring the environment was quiet and calm. Children were invited to attend for one session but were told that they could have breaks if they wanted. Each child completed the background measure (PLS-4) and then the eye-gaze control experiments in the same session wherever possible.

As previously, children were seated in front of the equipment with a familiar adult present. Where required some children sat on the lap of the familiar adult. The adult closed their eyes during testing to avoid influencing the eye-gaze system. The room was laid out with the eye-gaze system on one table, ensuring that sunlight was not shining directly onto the screen, as recommended in the manufacturer's specifications. Another table was used for the language assessment materials.

Table 5 - Chronological Age, Language Understanding Age Equivalents

Participant ID	Gender	Chronological Age (Months)	PLS-4 Language Understanding Age (Months)
P01	M	35	33
P02	F	32	30
P03	F	35	31
P04	F	34	32
P05	F	35	42
P06	F	35	31
P07	F	31	21
P08	F	35	35
P09	M	35	35
P10	M	35	31
P11	M	14	14
P12	M	22	19
P13	M	20	19
P14	M	23	18
P15	M	23	19
P16	M	32	29
P17	F	28	24
P18	F	34	33
P19	F	35	34
P20	M	28	19
P21	F	35	33
P22	F	32	23
P23	M	14	14
P24	M	20	20
P25	M	11	15
P26	F	33	29
P27	M	31	23
P28	M	30	19
P29	M	32	23
P30	M	34	31
P31	M	35	43
P32	F	20	23

The same eye-gaze control device used during the previous experiments was used again: a *MyTobii P10*, with the same specifications as detailed in Chapter 7. Children were positioned according to the best-practice guidelines published in the manufacturer's instructions (Tobii Technology AB, 2006): seated approximately 60cm from the screen with the child's eyeline falling within the top third of the screen. All test stimuli were presented within *Microsoft PowerPoint*, using Windows Control to access the onscreen items.

Sessions were video recorded for coding at a later date, although record forms were also completed for each child at the time of testing. Screen recording software was not used on this occasion, since timing was not measured in this phase of the study.

8.4.7 Calibration

Before using the eye-gaze control device to take part in the experiments, the device was calibrated for each child using the procedure described in the previous chapter.

8.4.8 Experimental Measure of Eye-Control

The experimental measure consisted of a cause and effect game with two different sets of animated stimuli, with two learning phases exploring the functions of effective and ineffective buttons, followed by a hybrid phase during which knowledge acquired was applied to complete a game (Figure 26). Each of the games featured animated characters dancing on the screen against a plain white background (see Figure 27 and Figure 28). In this round of experiments two versions of the game were created, in order to ensure that results obtained would not be influenced by children's preference for one animated character over another.

As with the previous experiment, children were not told at any point that the device was being controlled by their eyes but were informed before using the eye-gaze device that they were "going to play a looking game". During the experiment, children were verbally encouraged to "look" at the screen, without being given direct instructions about where on the screen they should be looking. Successful selections were reinforced with non-specific verbal feedback and praise to keep the child engaged in the activity.
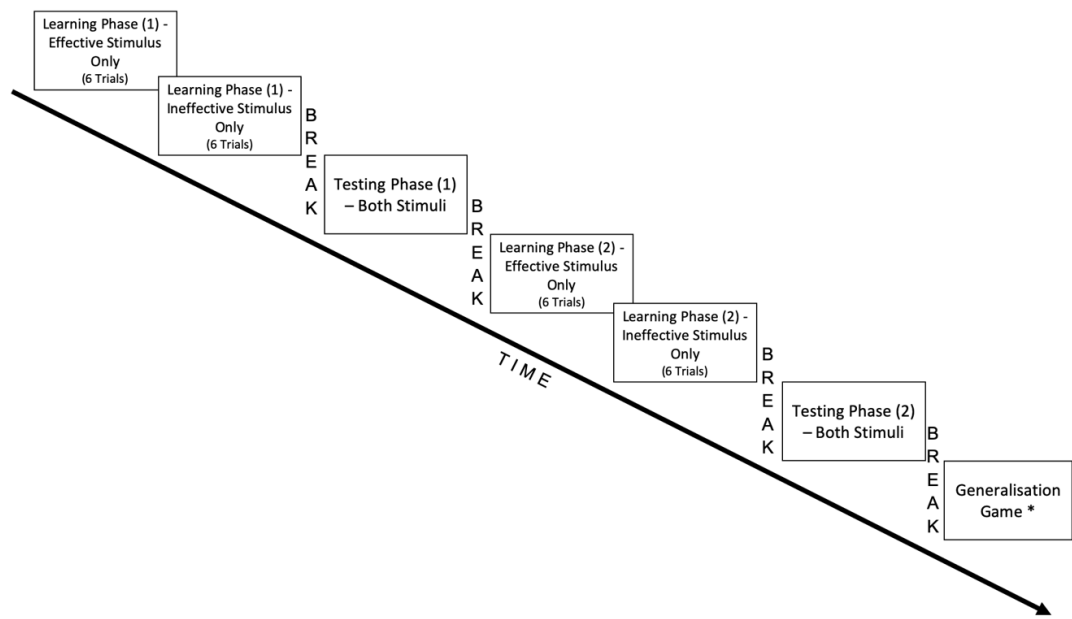
Figure 26 - Schematic representation of experimental procedure
(*Generalisation Game was non-compulsory, see Section 8.8)

Visual feedback regarding the location of the child's gaze onscreen was provided by a cursor in the shape of a crosshair which, when the child fixated on a particular point on the screen, would start the completion of the "dwell" selection. This had the same visual presentation described in Chapter 7 and once again completed over a period of 1.0 seconds. When the circle completed, the device would execute selection of whatever was located at the centre of the crosshair. An auditory *click* was included to further reinforce that a selection had been made.
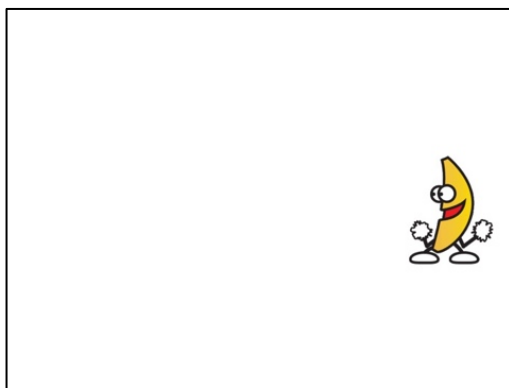
Figure 27 - Screen layout for the effective button learning phase, showing the effective button character against a blank background.
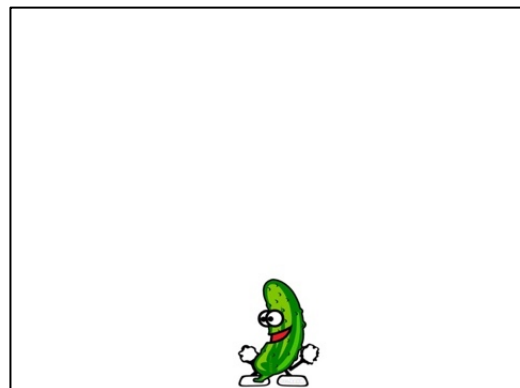
Figure 28 - Screen layout for the ineffective button learning phase, showing the ineffective button character against a blank background.

8.4.9 Effective Button Learning Phase

The first learning phase consisted of an animated character, a banana with arms, legs and eyes, presented on the screen against a blank, white background (Figure 27). The image appeared in one of nine locations on the screen. The stimulus was an animated graphical interchange format (gif) image with dimensions of 320 x 320 pixels, occupying 8° of visual angle at a distance of 60cm from the screen. The image looped through eight frames to give the impression of continuous movement, making it look as though the character was dancing. When the child fixated on the target for the 1.0 seconds required to complete the dwell, the banana would spin twice in a clockwise direction around a central pivot, before moving from its location to the centre of the screen in a straight line. Once there, the banana would disappear and be replaced immediately by a full-screen video, showing a short clip from an age-appropriate cartoon or TV theme tune (*Thomas the Tank Engine*, *Minions*, *Alphablocks*, *Aquanauts*, *Doc McStuffins*, *Chuggington*, *Balamory*), all of which played with sound. Control of the eye-gaze system was disabled whilst these videos played in order to prevent children accidentally activating the screen and moving on through the test before the reward phase was complete. Each clip played for a period of between 6 and 21 seconds before stopping and presenting the effective stimulus again in a different position. The effective stimulus was presented six times and children were required to activate it on each occasion in order to complete the full video and pass the first learning phase of the experiment.

8.4.10 Ineffective Button Learning Phase

Following the first learning phase, the experiment immediately and automatically advanced to the second learning phase. In this phase another animated character, a gherkin with arms, legs and eyes, was presented in one of the same nine locations to the effective button (Figure 28). The character was similar in design to the banana and was presented at the same size and dimensions but was visually differentiated by its colour. The character appeared on screen for six seconds, during which time looking at it for long enough to complete the dwell triggered no effect. After six seconds, the character would disappear and, after a gap of 2 seconds, would reappear in another location. This routine was presented six times. In order to ensure that children had learned that this ineffective stimulus did nothing, it was recorded when they made an attempt to activate it, so it could be demonstrated that they had seen this.

8.4.11 Hybrid Phase with Effective and Ineffective Buttons

After completion of the two learning phases, an interim screen appeared, in order that children could be given a break if required. Once children confirmed that they were ready to continue, the hybrid phase of the experiment was presented. In this phase, both stimuli appeared on screen at the same time in different locations (Figure 29).
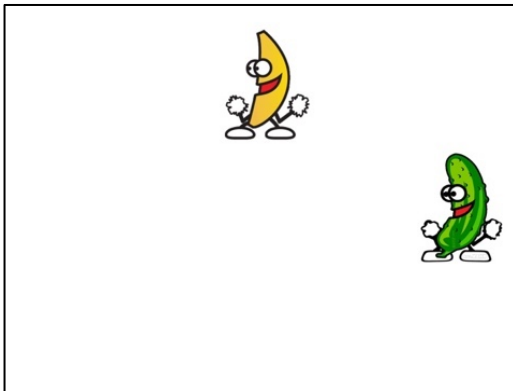
Figure 29 - Screen layout for the hybrid phase of the experiment, showing both the effective button (banana) and the ineffective button (gherkin).

Figure 30 - Reward screen for the hybrid phase of the experiment.

Fixating on the effective button caused the same actions as described in Section 8.4.9 above, with the character spinning and moving into the centre, followed by the playing of a fullscreen video clip. Fixating on the ineffective stimulus caused both stimuli to briefly disappear, before reappearing in the same positions once the child's gaze shifted to another part of the screen. A total of 12 presentations of this hybrid phase were made, with two videos of six parts each acting as the reward. At the end of the 12 presentations, a final reward screen was shown with a "well done" message, a further animated character (a dancing star with arms and eyes, Figure 30) and a short musical reward (a MIDI audio version of the opening bars of *Jackie Wilson Said* by Van Morrison). This was accompanied by verbal praise from the experimenter. In order that all children would see the reward screen, irrespective of how much of the experiment they completed, the experimenter could activate it at any time by pressing a key on a keyboard attached to the eye-gaze device.
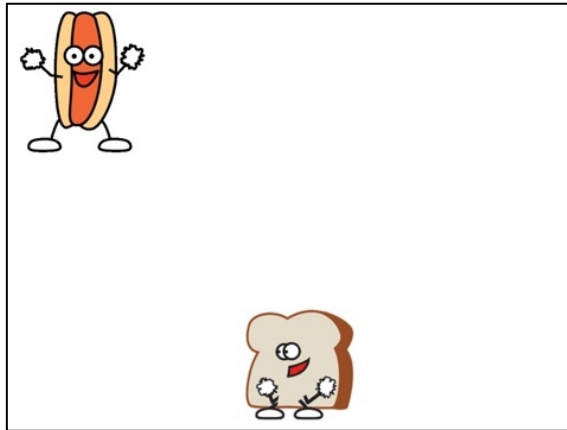
Figure 31 - The alternative presentation of the hybrid phase, showing the effective (hot dog) and ineffective (toast) buttons presented together.

8.4.12 Alternative Presentation

In order to ensure that children were learning the functions of the buttons and not merely responding preferentially to one or other character, an alternative version of the task was also designed with different animated characters: a hot dog replacing the banana as the effective stimulus and a slice of toast replacing the gherkin as the ineffective stimulus. Both the alternative characters were similarly styled and presented at the same size and at the same nine locations on the screen (Figure 31). The sequence of the alternative presentation was the same as that described in Sections 8.4.9 – 8.4.11 above, with two learning phases followed by a hybrid phase.

All children who participated in the study were asked to complete both versions of the task, with the order of presentation counterbalanced. Children were randomly assigned to complete either the "healthy" (banana and gherkin) or "unhealthy" (hot dog and toast) task first, before completing the other after a short break.

8.4.13 Generalisation Task

For children who completed all trials in the experimental task described above, a further, extension task was designed to provide some information about whether the skills and knowledge learned could be generalised and applied to similar but less visually engaging stimuli. In this task, the animated characters were replaced with two-dimensional images of each of the items taken from the ARASAAC symbol library (www.arasaac.org). Each symbol was presented against a white background with a square black border around it, demarcating

an area the same size as area of the animated figures in the main activity (Figure 32 and Figure 33).
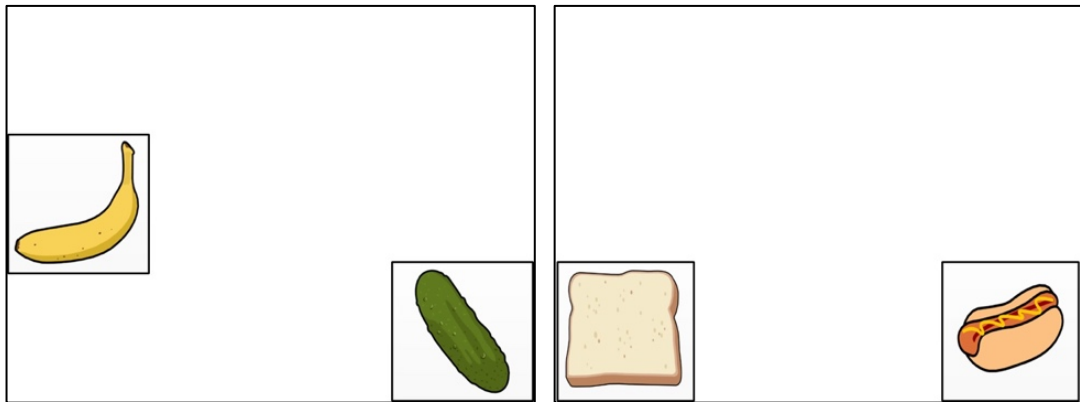
Figure 32 - Screen layout for the extension task ("healthy" version) showing the banana and gherkin symbols.

Figure 33 - Screen layout for the extension task ("unhealthy" version) showing the toast and hot dog symbols.

Children were presented with the version of the extension task that corresponded with the first version of the hybrid phase they had tried. Since the extension task was intended to test whether the skills could be generalised, no learning phase was included in this measure. The extension task contained the same video rewards as the experimental measure and was also presented 12 times with the stimuli appearing in different locations.

8.4.14 Scoring

Due to the varied number of trials that children had completed on the previous experiment, the decision was made to limit the total number of trials to 12 for each of the hybrid phases, a maximum of 24. With fewer trials and a more concrete "end point" to the experiments, children could better be encouraged to complete the full protocol. The scoring was redesigned to capture children's engagement and performance. Engagement with the activity was scored on the number of trials for which the child was visually engaged with the screen during each hybrid phase (total possible score = 24). Performance on the activity was measured by the percentage of the trials for which the child was engaged that resulted in correct selection of the effective stimulus.

During all phases of this experiment, the experimenter kept score using a printed score sheet (included in Appendix C-4). For each participant, the score sheet recorded whether they had

passed the effective learning phase (activating the effective stimulus six times) and the ineffective learning phase (making at least one attempt to activate the ineffective stimulus in order to see that this had no effect). Each of the 12 presentations of the hybrid phase was then scored by placing a "1" in the box if the child selected the effective stimulus, or a "0" if they selected the ineffective stimulus. As such, each child was given a total score out of 12 for each of the hybrid phases. Space on the form for collecting field notes was provided for the experimenter to record any observations of interest during the test session, including whether or not the child remained engaged with the task and any comments they made which were relevant to the task.

8.4.15 Analysis

Quantitative data collected during the study were analysed using IBM SPSS statistical analysis software (v 26.0.0). The data were analysed to investigate the following:

- Relationship between chronological age and language age equivalent
- Whether there was a relationship between order in which the games were presented children's performance
- Relationship between language age equivalent and child engagement
- Relationship between language age equivalent and performance
- Whether learning was evident within each game and between the two games
- Whether children's learning could be generalised to the less visually salient stimuli

8.5 Results

The qualitative observations made during the study and the results from the above analysis are presented below.

8.5.1 Calibration

All children recruited to the study (n = 32) were able to calibrate the device using the built-in calibration procedure described in the previous chapter.

8.5.2 Attrition

Five children (15.6%) completed the learning phases but could not complete any of the testing phase. Reasons for not continuing were similar to those observed in the previous

chapter with children either bring distracted or unable to retain focus despite prompting (n = 4) or repeatedly trying to touch the screen (n = 1). Analysis of these children reveals that once again they were amongst the youngest both chronologically (M_{age} = 21.8 months) and for language age equivalent (M_{lang} = 20 months). These children were removed from the final data analysis, leaving a group of 27 children included in the analysis described below.

8.5.3 Relationship between chronological age and language age equivalent

For the remaining children (n = 27), a Spearman's rank-order correlation was carried out to assess the relationship between chronological age (M_{age} = 30.3 months, SD = 6.57) and language age equivalent (M_{lang} = 27.19 months, SD = 7.30). Analysis of the data using the Shapiro-Wilk test indicated that language understanding age equivalent was normally distributed (p = .063), although chronological age was not normally distributed (p < .001). Hence the choice of Spearman's rank-order correlation for this analysis. Analysis also showed the relationship between the two sets of data to be monotonic, as assessed by visual inspection of a scatterplot. There was a highly significant correlation between language age equivalent and chronological age (r = .928, p < .001). Since language age was highly correlated with chronological age and language age was normally distributed, allowing for the use of more robust parametric tests, language age was used in subsequent analyses of engagement and performance.

8.5.4 Age-Matching between Groups

All children who engaged with the testing phases (n = 27) were asked to play both versions of the game. Children were divided into two age-matched groups: (Group A) attempting the "healthy" game featuring the banana and gherkin first (n = 13), and (Group B) attempting the "unhealthy" game featuring the hotdog and toast first (n = 14).

An independent-samples t-Test was conducted to determine if there was any difference in language understanding age equivalent between group A (M_{lang} = 24.92 months, SD = 6.93) and group B (M_{lang} = 29.29 months, SD = 7.22). There were no outliers in the data, as assessed by inspection of boxplots (Figure 34). There was homogeneity of variances, as assessed by Levene's test for equality of variances (p = .604). There was no statistically significant difference (t(25) = -1.598, p = .123) between the ages of children in the two groups.
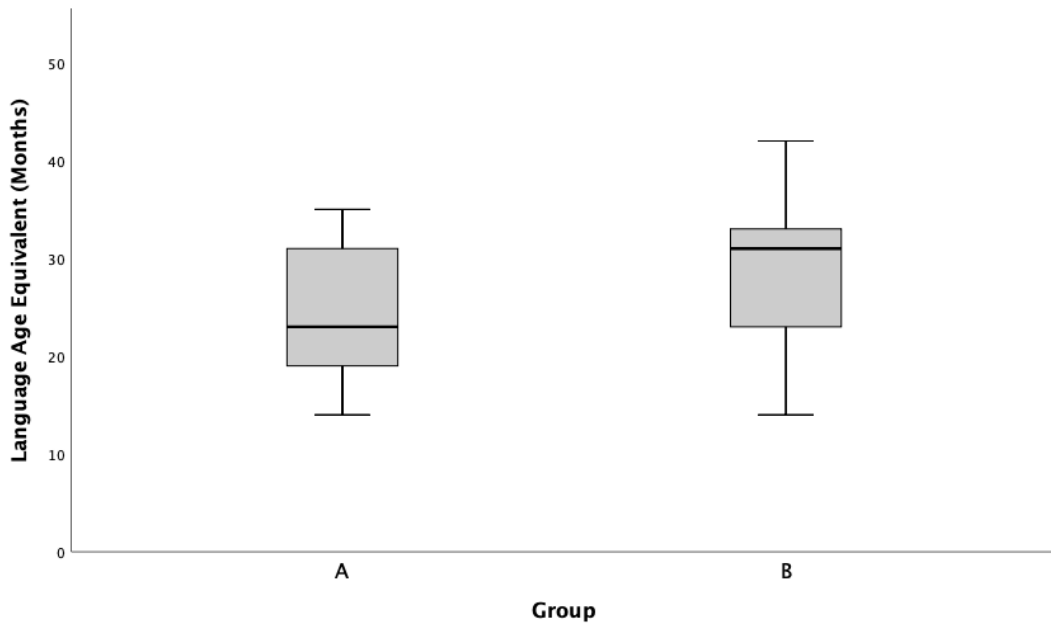
Figure 34 - Graph demonstrating the age distributions within the two groups

8.5.5 Relationship between language age equivalent and engagement

As discussed previously, each game consisted of 12 presentations of the stimuli, meaning a total of 24 possible presentations. The number of presentations for which each child was engaged ranged from 4 to 24.

The number of presentations was shown to be not normally distributed (p < .001) when tested using the Shapiro-Wilk test. Therefore, a Spearman's rank-order correlation was run to assess the association between language age and number of presentations with which each child engaged. A strongly significant correlation was observed between language age and the number of trials with which children engaged (r_s = .576, *p* = .002).

8.5.6 Engagement across both activities

All but one child that progressed to the second game continued to engage with the activities until the task was fully completed (see Figure 35).
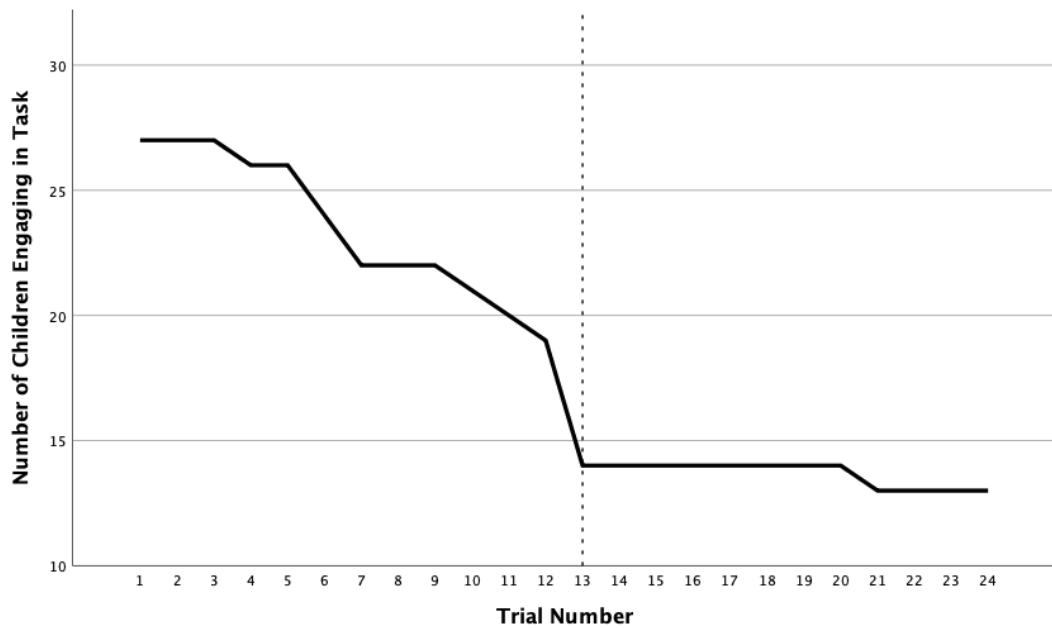
Figure 35 - Graph showing the number of children engaging with each trial, with reference line indicating the break between the two games. Note that this figure does not differentiate children that just looked at the screen during each trial, those that looked at the ineffective stimulus and those that looked at the effective stimulus to make a successful selection.

An independent-samples *t*-Test was conducted to determine if there was any difference in language understanding age equivalent between children who engaged with both testing phases (both games) (*n* = 14) and those who did not (*n* = 13). There were no outliers in the data, as assessed by inspection of a boxplot. Engagement scores for each level of gender were normally distributed, as assessed by Shapiro-Wilk's test (*p* > .05), and there was homogeneity of variances, as assessed by Levene's test for equality of variances (*p* = .213).

There was a significant difference in language age equivalent between those who only engaged in one game (*M*$_{lang}$ = 23.23 months, *SD* = 6.76) and those who engaged in both (*M*$_{lang}$ = 30.86 months, *SD* = 5.84), (*t*(25) = -3.143, *p* = .004).

8.5.7 Relationship between language age equivalent and performance

Both variables were normally distributed, as assessed by Shapiro-Wilk's test (*p* > .05), and there were no outliers. A Pearson's correlation was run to assess the relationship between children's language age equivalent and the percentage of effective stimulus selection. All 27 children were included in analysis.

There was a no significant correlation between language age equivalent and number of correct activations ($r = 0.221$, $p = 267$).

Of note here is the analysis of one particular case – P05 – who achieved the highest score in the group on both games. This child also had the highest language age equivalent score (42 months) and was chronologically one of the oldest children (35 months).

8.5.8 Impact of Presentation Order on Performance

A further examination of whether the order of presentation influenced overall child performance (i.e. the number of times a child chose the effective stimulus for testing phases 1 and 2 only) between the groups. Due to the varying number of trials with which each child engaged, results were converted to percentages for both group A (M_{stim} = 54.05%, SD = 9.6) and group B (M_{stim} = 62.37%, SD = 16.70). Outliers were retained in the analysis of boxplots identified four outliers, all in group B (Figure 36) and so, since it was not considered appropriate to remove these scores, a Mann-Whitney U test was run to determine whether there were differences in success rates between the two groups. Distribution of correct scores was similar for both groups as assessed by visual inspection. Median correct score was not statistically significantly different between groups A and B (U = 125, z = 1.679, p = .105). Presentation order therefore did not affect the number of correct selections.
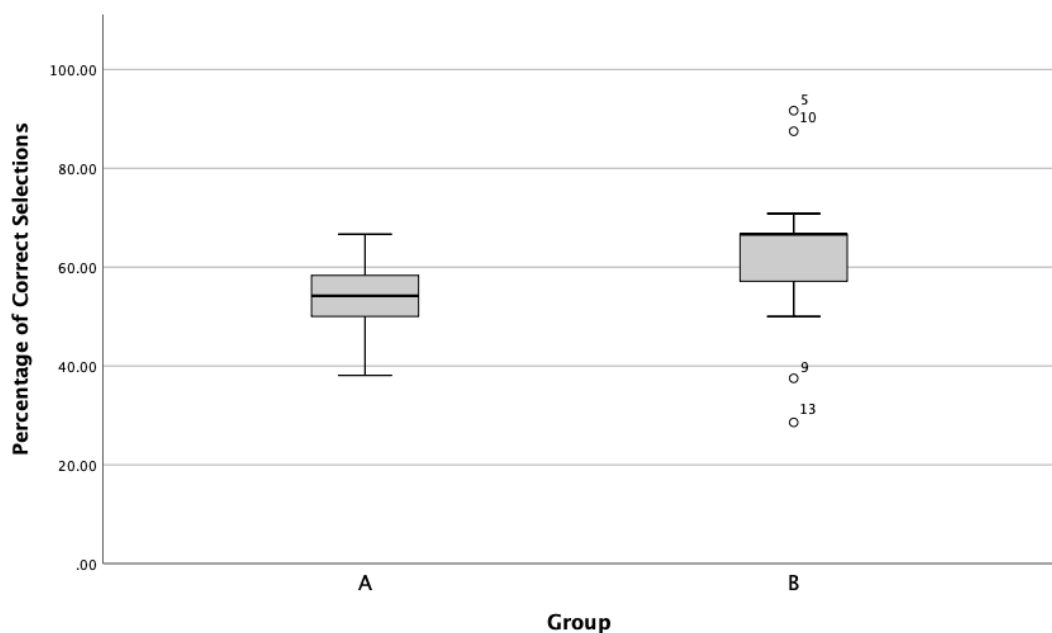
Figure 36 - Graph showing the percentage of correct trials for each group.

8.5.9 Presence of a learning effect

As participants moved through the game, it was anticipated that they would show a learning effect – fixating more often on the effective button as familiarity with the task increased. In order to test this, the group of children who engaged with all 24 trials (n = 13) were plotted on a line graph showing the number of children selecting the effective stimulus in each trial (Figure 37). The graph does not show the expected upward trend, indicating that a learning effect was not present across the game.
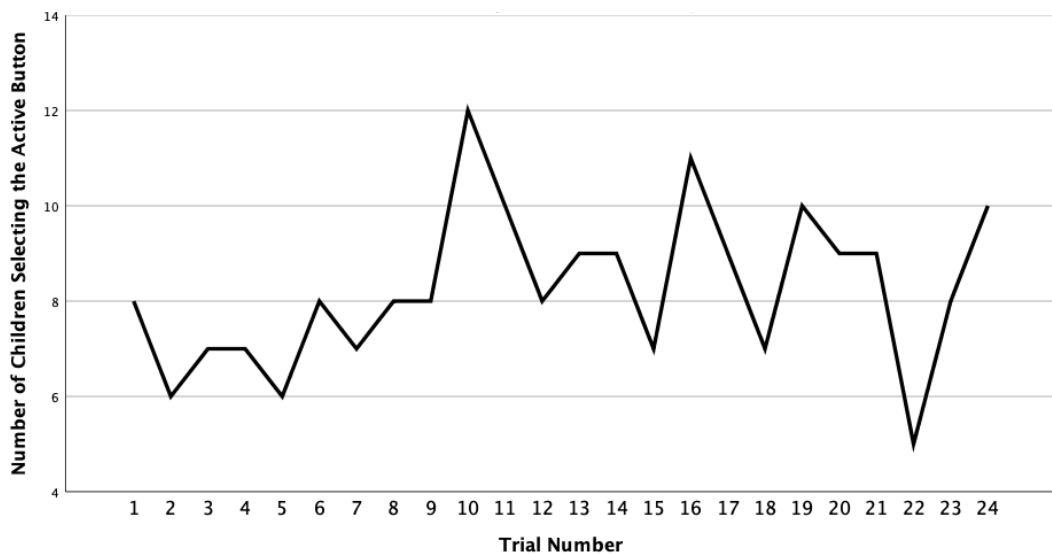
Figure 37 - Number of children selecting the effective stimulus by trial number

To further investigate this, the performance of each of the children completing all trials was examined by comparing their score on the first game with their score on the second. The results are summarised in Table 6 below.

A paired-samples t-Test was used to determine whether there was a statistically significant mean difference between scores on the first and second games. Three outliers were detected that were more than 1.5 box-lengths from the edge of the box in a boxplot. Inspection of their values did not reveal them to be extreme and they were therefore kept in the analysis. The assumption of normality was not violated for score on the first game (p = .531) or score on the second (p = .904), as assessed by Shapiro-Wilk's test. Children performed slightly better on the second game (M_{score} = 7.77, SD = 1.83) than on the first (M_{score} = 7.31, SD = 2.18), however this difference was not significant (t(12) = -.822, p = .427).

Table 6 - Change in score between first and second game

Participant ID	Score on First Game (/12)	Score on Second Game (/12)	Change
P01	4	9	+5
P05	11	11	0
P06	6	8	+2
P08	6	6	0
P09	5	4	+1
P10	11	10	-1
P18	8	6	-2
P21	8	8	0
P22	8	8	0
P28	7	7	0
P29	9	8	-1
P30	7	7	0
P31	5	9	+4
Mean	7.31	7.77	+0.62

8.5.10 Generalisation

All children who completed both hybrid phases were asked if they wanted to take part in a further activity looking at the generalisation of the skills they had learned. A group of 9 children (M_{age} = 32.44, SD = 4.95) agreed to continue and took part in this phase. This represented 69.2% of those completing both hybrid phases.

A one-way repeated measures ANOVA was conducted to determine whether there was a statistically significant difference in scores on the three phases. There were no outliers and the data were normally distributed for each phase, as assessed by boxplot and Shapiro-Wilk test (p > .05), respectively. The assumption of sphericity was met, as assessed by Mauchly's test of sphericity ($\chi^2(2)$ = 4.17, p = .124). The results on the three phases did not differ significantly ($F(2, 16)$ = .374, p = .694, ηp^2 = .045) with scores similar across the group in the first game (M_{score} = 7.22 SD = 2.64), the second (M_{score} = 8.11 SD = 2.09) and the third (M_{score} =

7.56 *SD* = 3.13). This finding suggests that children who completed the two main testing phases were able to generalise the skills learned to new, less visually exciting stimuli.

8.6 Discussion

This chapter addressed three research questions:

1. Do the changes made to the experimental design allow more younger children below 32 months to engage with the task?

2. Does a learning effect exist as children become more familiar with the properties of the stimuli presented?

3. Can children who demonstrate sufficient engagement and sufficiently well-developed cause and effect skills to complete a game with highly motivating stimuli generalise these skills to matched, less "exciting" stimuli?

The results presented here seem to provide additional weight to the idea that developmental level plays a significant role in whether or not established cause and effect with physical objects can be transferred to a task using eye-gaze technology. In a similar pattern to the previous experiment five children did not engage with any of the experimental measures, all of whom were developmentally under 24 months.

Despite this the first research question, that of whether a change of stimulus and reward design would allow developmentally younger children to engage, appears to have been answered affirmatively. Ten children with a developmental age of 24 months or less were able to engage with at least some of the activity. Further, for the trials in which children engaged, there was no significant relationship between language age and percentage of correct selections. Analysis of the field notes collected indicates that children in the younger group required more prompts to refocus than their older peers. This finding may be explained by the body of literature on young children's susceptibility to both social and non-social distractors which states that as children age, so their level of distractibility decreases (López, Menez, & Hernández-Guzmán, 2005), and they achieve better "inhibitory control" (Ruff & Lawson, 1990). It is proposed that the redesign of the experiments has made them more

engaging for younger children, but they may still require more support to engage with the activities for long enough to learn how to control an eye-gaze system.

Another interesting outcome of this experiment is the significant difference in developmental age between the children who completed one game and those who completed two games, which also suggests that children with a higher developmental level are better able to engage with tasks of this type. Similarly, children with higher developmental levels completed more individual trials. Therefore, it seems reasonable to state the children's engagement with the activity increased in line with their developmental level.

As this experimental protocol did not include any specific measures of children's attention, it is difficult to say from these results whether the difficulties that some children experienced in engaging with the activity were due to generalised difficulties maintaining attention and focus or to something task specific. However, it is possible that the literature in this field may be helpful in placing the findings in context. Whilst it is well known that the length of children's sustained attention increases with age (Cuevas & Bell, 2014; Ruff & Capozzoli, 2003), of more relevance to this thesis is the change in the nature of this attention. Several studies have shown that, as children approach three years old, they spend more time focusing on construction and problem solving than their younger counterparts (Ruff & Lawson, 1990). This may have relevance to the observed performance of children in the first two studies described in this thesis, since the older children have shown greater levels of engagement but may have been better able to problem solve and work out for themselves how the eye-gaze system functioned.

As such, these results would sound a note of caution for those introducing eye-gaze technology to developmentally younger children. Whilst children with a developmental age of lower than 24 months can engage in such activities, they are likely to be slower to master them and their performance may not be as strong as those with developmental levels of 32 months and above. Equally, all children who were not able to take part in this task were below this developmental age, indicating further variability in their engagement and performance. The challenges with engagement may point, clinically, towards introducing the technology in shorter sessions to maximise the time for which younger children can engage

with the tasks. It is also likely that younger children will require extra support to focus and learn the processes by which control of an eye-gaze system can be affected.

The second research question addresses whether a learning effect existed across the duration of the experiment. This does not appear to be the case, with the group's performance not increasing in a consistent way as might be expected. As such, even though the redesign made to the experiments has increased children's levels of engagement, performance still appears to fluctuate. A small increase in the performance of the group who completed all 24 trials is noted if one looks at the number of children who correctly activated the effective button on the first (n = 8) and last (n = 10) trials and at the mean scores of all of these children on the first (M_{score} = 7.31, SD = 2.18) and second (M_{score} = 7.77, SD = 1.83) games. However, these small increases mask a large variability in performance; with between 5 and 12 children correctly activating the effective button at different stages of the task. This finding is similar to that recorded in the previous chapter.

This raises another important point for consideration in this thesis. Where eye-gaze teaching packages are built on progression through a continuum of skills, comparatively little attention is paid to the potential variability of performance within each of those skills. As such, children may reach a threshold where the software determines that they have "achieved" a particular skill and are ready to move on to the next one. From the data recorded here, it would be difficult to say that all children had truly consolidated the skills required for control of this activity. This provides another important learning point for those seeking to implement this technology with younger children. Whilst the activities and games within an eye-gaze training package may be a useful tool, results provided by these packages should be interpreted with caution – particularly when they are based on algorithms not made available to those implementing them – and they should not be used as a substitute for careful observation of a child's skills.

Taken together, the requirements to focus children on engaging with the task and their variability in performance across the games highlight one factor that has not been considered thus far as a potential contributor: that of external input from a teacher or play partner. In the tasks described in these first two experimental chapters, the focus has been on children's ability to intuitively reason how the device is controlled and then to apply this knowledge to

completion of a game. However, the use of assistive technology, and in particular AAC, requires explicit teaching. The challenges of teaching eye-gaze technology have been previously discussed in Chapter 2, with there being no useful way to physically model or demonstrate the use of the technology to children. Clinical experience suggests that children are never introduced to the technology in isolation, always having a teacher or adult with them during sessions with the technology. The perceived importance of teaching and training when introducing this technology is underscored by the outcomes of a recent Delphi study (Karlsson et al., 2020, submitted for publication), where stakeholders including clinicians, educators, parents and device-users all ranked teaching and instruction from competent professionals as highly important.

The third research question of whether the skills learned could be generalised back to less interesting stimuli appears to also have been answered, with children who completed both of the games in the main experiment able to transfer the skills learned into a novel task with no additional learning phase to habituate them to the new stimuli. Once again, it is important to note that children who completed this experimental phase were developmentally the oldest in the group (M_{age} = 32.44, SD = 4.95), adding further weight to the importance of understanding a child's developmental levels when considering eye-gaze technology, or indeed any other access method.

8.7 Implications for Future Work

This study and its predecessor have focused on the ability of children to intuitively master the use of eye-gaze technology. The results have established with some level of confidence that children above 32 months developmental age are able to do this and that children below 24 months have more difficulty. However it remains the case that some children with cerebral palsy who are considered for eye-gaze technology are at a developmental age lower than this, so it is important to consider whether any further experimental redesign might support their engagement with the task and, by extension, their learning to use the technology.

One logical next step is to look at the impact of teaching and training from a human partner. Given the perceived importance of teaching when first introducing eye-gaze technology, and the inherent difficulties in implementing this with younger children who may not be able to

understand the concepts and language needed to explain the technology, looking in more detail at the impact of explicit teaching will provide more evidence on how this complex technology might best be introduced to younger children. Therefore, the next chapter will look at the introduction of a teaching phase, in order to examine the impact of this on performance and engagement.

The redesign of the experiments has been successful in reducing the developmental level required to engage with the activities. This increase in the salience and "excitement" of both the stimuli and the reward have moved the design of these experiments closer to many of those included in eye-gaze teaching packages. However, spatial dislocation of the causative trigger and the resulting reward is still a possible confounding factor in children's performance. A further redesign of the experiments is therefore proposed to bring the onscreen elements of the stimulus and reward together so that they will be spatially congruent. It is also proposed that eliminating the post-selection movement of the stimulus (spinning and moving the effective target once activated) will provide better temporal continuity between the trigger and the action.

Additionally, up until this point, children have been using larger targets and the inbuilt cursor control provided by the eye-gaze control systems used. As has been previously noted (see Chapter 2), many training packages include in their early stages some level of scaffolding or support from the software. Returning to the Human Activity Assistive Technology (HAAT) Model (Cook & Hussey, 1995; Cook et al., 2014), this support essentially increases the role of the technology as an extrinsic enabler, with several functions moving from the Human portion of the model to the Assistive Technology part. In Chapter 2 of this thesis, a question was raised about how this might be affected without taking agency away from the child; that is to say, how might features of the technology be leveraged to support learning, without increasing the risk of a false positive result or making the activity into a "no fail" exercise? The following chapter explores this by introducing some of these supports.

Finally, the experiments described so far have focused solely on eye-gaze technology, making the assumption that this technology is harder to learn for these children than other equivalent direct access methods. The next chapter, therefore, introduces a comparison

experiment using a touchscreen to complete the same task and to explore whether the pattern of difficulties that have been observed so far are particular to eye-gaze technology.

Chapter 9

Analysing the impact of teaching on performance in an eye-gaze control cause and effect task

9.1 Introduction

The experiments described in the previous two chapters have indicated that children with a developmental age of below 32 months have a varied pattern of engagement and performance when learning to complete a novel eye-gaze task. Whilst changes to the experimental design enabled participation in the activities by children of 24 months and even younger in the activity, their engagement with the activity and their subsequent application of the skills learned was reduced compared to their older peers.

Whilst these findings raise questions about the potential utility of eye-gaze teaching and training software for developmentally very young children, they also present a further area of study: the need to examine the impact of teaching and training from people supporting the eye-gaze user. As discussed in Chapter 2, some emerging evidence exists (Borgestig et al., 2016) that supports the impact of teaching and training on a child's acquisition of the skills needed to make use of eye-gaze control technology. This study, whilst establishing the need for extensive teaching and training (an average of 15 – 20 months was required to show improvement in speed and accuracy) did not set out a protocol for the teaching and training given to these children. It is recognised in the fields of augmentative and alternative communication (AAC) and assistive technology more broadly that teaching and practice are important components in developing operational competence and purposeful control of a device (Campbell, Milbourne, Dugan, & Wilcox, 2006; Light & McNaughton, 2014a; Marina et al., 2012). It is perhaps not unreasonable to assume, given the results obtained so far and the differences in haptic and proprioceptive feedback discussed in Chapter 4, that the learning demands of eye-gaze technology may be higher than for other access methods. As discussed in this chapter, explicit verbal instruction using causal language is the best available option for those wishing to teach eye-gaze technology.

In addition, the studies carried out in this thesis so far have focused solely on the use of eye-gaze technology, without making any direct comparison with other methods of access. Such comparisons will be necessary in order to better understand whether it is the eye-gaze technology itself, or the specific activity, that children in this study are finding challenging. Whilst the hypothesis remains that there is something specific about eye-gaze technology that will make it harder for children to learn, even with instruction, the comparison with another access method will be informative in demonstrating that children are able to complete the activities with an access method that provides greater feedback and is more spatially contiguous between action and result.

This chapter therefore addresses two areas of study – looking at the impact of explicit instruction and teaching on children's performance and comparing their performance with eye-gaze to performance with the same activity using a touchscreen.

9.2 Causal Language Instruction

For the younger children who have so far displayed the most difficulty, the use of "causal language" to support their understanding of the technology merits some investigation. The causal language approach adopted in this experiment is similar to that used by Bonawitz and colleagues, who defined it as language used to comment on and subsequently instruct infants about the nature of causal relationships. The researchers describe causal language as being simplified so as to be accessible to young children: using core verbs and simplified grammatical forms. They hypothesised that such use of language could support children in two respects. Firstly, the use of consistent verbs and verb forms across observation and instruction ("The block makes the truck *go*" to be followed by "Can you make the truck *go*?") may help to embed the causal links between objects and actions. Secondly, the use of such language could support children merely by reinforcing for them that the relationships they perceived were indeed causal. The researchers in this study identified that children of 24 months of age were significantly more likely to complete a cause and effect task when exposed to causal language instruction than those who were given non-causal instructions or no instructions at all (Bonawitz et al., 2010).

Given that the mean age of children in the Bonatowitz study is similar to those children who have been demonstrating greater difficulty engaging with and completing tasks using eye-

gaze technology, investigating the use of causal language to support these younger children is warranted.

9.3 Selection of a Comparison Access Method

Another interesting question raised by the experiments reported so far is that of how performance on an activity carried out using eye-gaze control technology compares with the same activity controlled via a different access method. This chapter therefore compares eye-gaze access use with the use of a touchscreen. The choice of a touchscreen as the comparison access method was made because it is a selection method that is analogous to eye-gaze control; being a direct access method with no intermediary components such as a mouse, joystick or stylus. As alluded to previously, a touchscreen provides the user with a much greater level of proprioceptive feedback, making it the ideal choice as an access method against which to compare the use of eye-gaze technology.

The use of a touchscreen as a comparative access method does present one obvious drawback: the technology has become near-ubiquitous over the past two decades. The Office of Communications' (Ofcom) annual survey of technology use and attitudes found that around 20% of 3 – 4 year old children have their own touchscreen device (smartphone or tablet), 58% of 3 – 4 year olds and 76% of 5 - 15 year olds using a touchscreen device regularly at home for internet access and playing games (Ofcom, 2018). Over half of 3 – 4 year olds (52%) spend over nine hours each week online, with the majority making use of a touchscreen device to do this (Ofcom, 2018).

It is not unreasonable to assume that children in the age range targeted by this section of the study would have prior experience with a touchscreen. In order to minimise the impact of this likely familiarity on the results, the decision was taken to use a touchscreen that could be modified to include an activation delay, so that children would need to learn the specifics of its use. This is described in Section 9.6.7.

9.4 Experimental Design

This section of the thesis uses a repeated measures, two-by-two design, in which participants were divided into two, age-matched groups and used the two access methods (touchscreen and eye-gaze control) in a counter-balanced procedure to ensure that the order of

presentation did not have an impact on the outcome. The activities were the same on both access methods. In this study, children underwent similar learning and baseline testing phases to those used in previous experiments, but the study was extended to include an additional intervention phase, where children were explicitly taught how to use the device, and a post-intervention phase during which they were tested again to observe the impact of this teaching on their performance.

The experiments described in this chapter therefore take the access method (eye-gaze or touchreen) and the testing phase (baseline, intervention, post-intervention) as independent variables and the number of effective stimuli activations as the dependent variable.

To reduce the impact of fatigue caused by the extended testing protocol, children's language and developmental ages were not assessed as part of the experimental protocol. As the previous two experimental phases have demonstrated that language, developmental and chronological age are very highly correlated in typically developing children, it was considered appropriate to remove these background measures in order to allow for a longer testing phase. In order to demonstrate that the children included in the study had an established understanding of cause and effect with real objects, a brief play-based task was included. This task also served to introduce children to the testing environment and to the experimenter in a relaxed and unintimidating way.

9.5 Research Questions

The core research aims of this chapter are to explore the impact of teaching on performance and to contrast the performance of children using eye-gaze control technology with performance using a touchscreen. To consider these aims, this chapter addresses the following research questions:

1. Can typically developing pre-school children learn to better use eye-gaze control technology after explicit teaching and instruction using causal language?

2. Do typically developing pre-school children perform better in cause and effect tasks when using touchscreen technology than when using eye-gaze control technology?

Given that it is likely children included in this study will have previous experience and familiarity with touchscreen technology, it seems equally likely that they will perform better with this access method than with the new, novel eye-gaze control technology. However, it may be that instruction in this new access method will help children to learn its function and that this will in turn reduce the gap in performance between the two access methods. Therefore, a third research question is proposed:

3. Will the likely performance disparity between performance on touchscreen and eye-gaze control tasks decrease after explicit teaching and instruction?

9.6 Methods

The following sections describe the methodology of this first group of experiments, as well as the participants and recruitment strategy.

9.6.1 Participants

This phase of the study recruited 18 typically developing pre-school aged children. However, four children were not able to participate due to absence from nursery on the testing days, meaning only 14 children were included. This group (3 male, 11 female) were aged between 20 and 35 months (M_{age} = 28, SD = 4.93).

9.6.2 Recruitment

Children were recruited from two pre-schools in the south east of England. All children recruited to the study met the core inclusion criteria of having no diagnosed learning disability, understanding English to a level sufficient to understand the instructions (as reported by staff), and having no reported hearing or vision difficulties (other than refractive errors corrected by glasses). The managers of each pre-school agreed to the children's taking part and distributed information sheets (Appendix D-2) and opt-in consent forms (Appendix D-3) to parents of children meeting the above criteria. Parents were told that they may withdraw their children from the study at any point. Verbal assent was gained from each child at the start of each testing session by asking them if they were happy to play some games with the experimenter. This was reaffirmed at various points during the session and children were permitted to opt out or to take breaks at any point.

9.6.3 Ethical Approval

Ethical approval for this section of the study was granted by University College London Research Ethics Committee, as an amendment to the ethical agreement used in the previous chapter (Project ID 1328/009). The extension detailed the changes to the experiment design and the addition of the teaching phase and an additional testing phase. A copy of the ethical approval is included in Appendix D-1.

9.6.4 Equipment and Testing Environment

All children were tested in a separate, familiar room in their pre-school. Distractions were minimised by hiding and covering other toys and activities present in the room, by closing the curtains, and by ensuring that the environment was quiet and calm. The testing area contained a table, with the eye-gaze control device and the cause and effect toy positioned on it, and a chair of appropriate size for the children participating in the experiments (Figure 38). The eye-gaze control device was initially covered up when children entered the testing environment, so that the cause and effect task with the toy could be completed first and without distraction. The eye-gaze control device was again setup according to the manufacturer's instructions and positioned so that it was not in direct sunlight.

Figure 38 - The layout of the room when each child entered the testing area.
The eye-gaze device is positioned on a stand and covered until the experiment is ready

For this experiment, a different eye-gaze control device was used, in order to be compatible with the software in which the experiments were written (see below). The new device was selected to be as similar as possible to the device used in previous experiments. The device chosen was the *Mobi 2* from *Jabbla*, which was loaned to the project by the manufacturer's UK supplier, *Techcess Ltd*. The *Mobi 2* device has a smaller screen size (12"), with the same aspect ratio and resolution as the *MyTobii P10* used in the previous experiments (4:3 aspect ratio, 1024 x 768 resolution). This device had a *Tobii PCEye Go* eye-gaze camera, the updated form of the camera found in the *P10*, attached via a specially made bracket below the screen. Such a configuration is common to many AAC devices.

As with previous experiments, the device was positioned so that children would be seated at the distance from the screen specified in the manufacturer's usage instructions - approximately 60cm away with the eyeline in the top third of the screen area. The device was mounted on an adjustable arm, allowing it to be positioned to ensure the correct height, distance and angle for each child. The positioning guide was used to ensure that the device was correctly positioned relative to the child. The *Tobii PCEye Go* camera has a similar trackbox area to the *MyTobii P10* at 30 x 20 x 20 cm (W x D x H), therefore permitting some degree of head movement so that children were not required to sit completely still.

The *Mobi 2* also includes a touchscreen, allowing the same device to be used for both access methods. It was chosen in part because it uses the older "resistive" touchscreen technology, which differs from the "capacitive" technology on which most modern phones and tablets are based. A resistive touchscreen is activated by mechanical pressure from the finger or a stylus, meaning that it requires more force to activate than a capacitive screen, which operates by sensing changes in voltage caused by the interaction between a finger and the screen, and so can be activated with a much lighter touch. Owing to the fact that resistive touchscreens are much less frequently used in commercial products, it was reasoned that most children in the study would be less familiar with them.

The *Mobi 2* runs the *Mind Express 4* (ME4) communication software, and this software was used to write the experiments described in this chapter, since it allows for the presentation of videos at a specific location on the screen, rather than in full screen. This meant that the

reward video could be presented at the same location as the stimulus that triggers it, reinforcing the cause and effect relationship. A piece of code was written, using the *Python* coding language, to randomise the position of the stimuli and ensure that the video played in the same location as the stimulus which triggered it. This code is reproduced in Appendix D-5.

9.6.5 Procedure

Children were invited into the room one at a time, with each accompanied by a familiar adult. Adults accompanying the children were asked not to provide any specific instructions for the task but were told that they could give encouragement or reassurance as required. Verbal assent was received from each child prior to commencing the experiment. Children were randomly assigned to one of two groups (eye-gaze-touchscreen or touchscreen-eye-gaze) which were adjusted to be age-matched as best as possible. The groups pertained to the order in which children completed the experimental tasks. The basic experimental procedure is summarised in Figure 39 below.
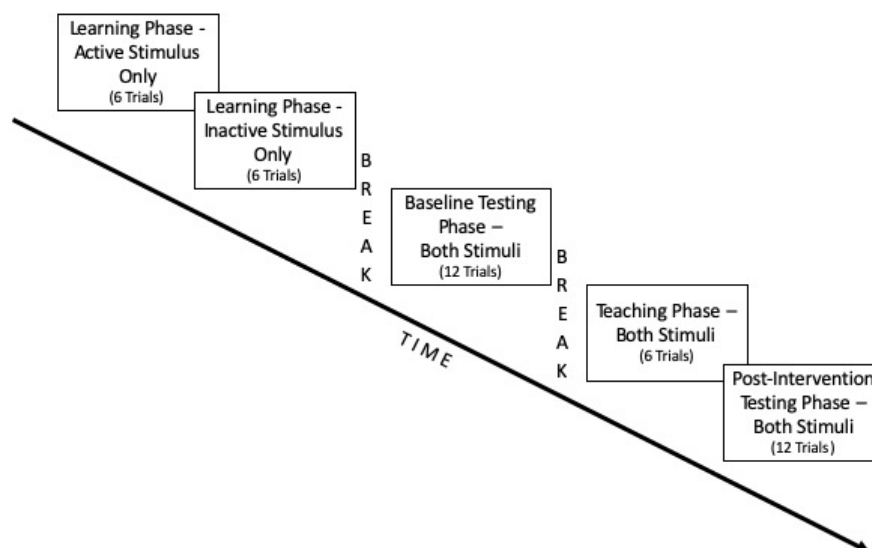
Figure 39 - Schematic diagram of the experimental procedure. This procedure was replicated twice for touchscreen and eye-control modalities.

9.6.6 Background Measure

In order to demonstrate that children had an established understanding of cause and effect for physical objects, a game using a cause and effect toy was played at the start of the session.

Whilst cause and effect understanding had been reported for all children in the previous chapters, it was decided to confirm it with a simple game, which also served as an "ice breaker". This decision was taken since cause and effect understanding would need to be confirmed for the group of children with cerebral palsy, hence the inclusion of this task here. The experimenter modelled use of the toy, pushing a button to make it move across the table and accompanying this with a causal language observation such as "The button makes it go". It was then passed to the child, with the prompt "Can you make it go?", followed by non-specific spoken encouragement. Each child was given up to one minute to demonstrate use of the toy. This method has been used to demonstrate evidence of cause and effect in typically developing children of around nine months (Sharma et al., 2008), meaning all children in this study should be able to meet the demands of the task and demonstrate their understanding of cause and effect using objects.

9.6.7 Calibration, Feedback and Touchscreen Configuration

Calibration of the eye-gaze device was not carried out ahead of these experiments. This decision was taken in an attempt to engage children immediately in the target activity without the need to go through a separate and less motivating procedure beforehand. Adjustments made to the experiments, with larger targets and targeting assistance from the software as detailed below, meant that the device could be used without the need for an accurate calibration, meaning all children were able to use the default settings. Observation of children during this part of the study confirmed that all children could make selections using the eye-gaze control without a calibration in place.

The use of *ME4* software allowed several changes to be made to the experiments to help children in inferring that they were in control of the device. Firstly, the use of a function often known as "snapping" was employed, where any fixation occurring within the target area is aggregated to provide greater efficiency of control for users. This reduces the accuracy demands placed on users, although it does not provide false positive results, since only gaze points falling within the target area are included in the snapping algorithm and gaze points falling in neighbouring screen areas are excluded. Secondly, the enhanced visual feedback which could be provided by *ME4* was leveraged to support children in making accurate selections. As discussed further below the screen was divided into nine areas ("cells"), with divisions not visible to the child. When the child's gaze point (indicated by the same crosshair

cursor used in the previous experiments) was registered within any of the areas, a red border appeared around that area to reinforce that this was where the child was looking. This increased level of feedback about where a child is looking was provided to further support children in inferring their control of the system. Both snapping and the use of highlighted borders are used commonly in computer access and augmentative and alternative communication (AAC) software. Neither adjustment was considered to impact the overall goal of the experiments, since neither guides the child towards making the correct selection. Instead, both adjustments support the child in more easily making the selection once they have themselves determined how to control the system.

During the eye-gaze trials, the touchscreen was deactivated using the *ME4* software, meaning that touching the screen would not affect the task.

Whilst no calibration was required to use the touchscreen, the device was setup with a similar "dwell" selection to that used in the eye-gaze condition, in order to ensure that pre-existing familiarity with a touchscreen did not play a role in children's performance. This meant that the child was required to touch and hold on a cell for 1.0 seconds before a selection was registered. Progress towards selection was indicated by a completing circle displayed in the centre of the stimuli, replicating the eye-gaze dwell selection. The same red border used in the eye-gaze tasks was also used in the touchscreen tasks.

9.6.8 Learning Phase

As with previous experiments, children were initially presented with six consecutive trials showing only the effective stimulus, followed by six trials with only the ineffective stimulus. In this experimental condition, the effective stimulus was a photograph of a female adult wearing a brightly coloured blue t-shirt, smiling and looking directly at the child, positioned against a blank background (Figure 40). The ineffective stimulus was a photograph of a male adult wearing a yellow t-shirt, also smiling and looking at the child, positioned against a blank background (Figure 41).

Photos of real people replaced the animated characters from the previous experiment as it was simpler to provide continuity between the stimulus and its resulting action. In the previous experiment, the stimulus had triggered a response that had no relation to its form

or content. It was decided in this experiment that using a stimulus that triggered a video showing the same characters, in the same scene and played at the same onscreen location would provide further reinforcement of the causal relationship between trigger and reward.

Figure 40 - Effective stimulus - a woman in a blue t-shirt against a neutral background

Figure 41 - Ineffective stimulus - a man in a yellow t-shirt against a neutral background

Both stimuli were randomly assigned to one of nine, equally sized areas of the screen, meaning that they both had an effective area of 6.5 x 5.0 cm (20° x 17° of visual angle at 60cm distance). When selected, the effective stimulus played one of six randomly selected five second video clips of the female adult completing a novel task, such as playing with a toy or blowing bubbles, each with accompanying sound (Figure 42). The video played in the same area of the screen and at the same size as the stimulus that triggered it. Attempting to select the ineffective stimulus had no effect and it remained on screen for six seconds, before disappearing and reappearing at another location after a delay of two seconds.

Figure 42 - Still from one of the reward videos used in the experimental measures

As previously, only minimal verbal prompting was given during this learning phase, with the instructor only using prompts to direct the child's attention to the task. For the touchscreen condition, children were encouraged to press the screen harder if they did not achieve enough pressure to activate the resistive screen. They were not given information about the need to hold their finger on the screen until the dwell had completed.
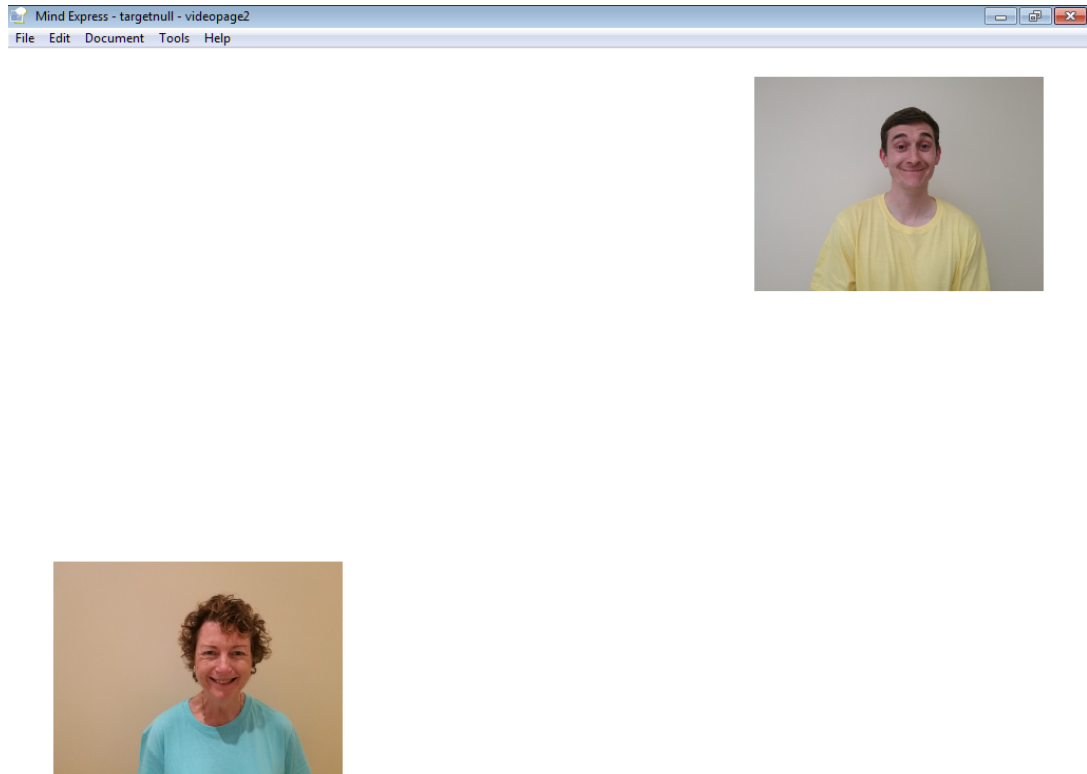
Figure 43 - Sample screen from the baseline and post-intervention testing phases, showing the target stimulus (blue t-shirt) and the ineffective stimulus (yellow t-shirt) displayed together.

9.6.9 Baseline Testing Phase

Following the two learning phases, children completed the first hybrid phase, where both the effective and ineffective buttons appeared on the screen together (Figure 43). When the child selected the effective button, they were again rewarded with a randomly selected video as described above. If they selected the ineffective icon, the screen would go blank for two seconds, before displaying the buttons again in two different, random locations. If the child made repeated selections in blank areas of the screen, the experimenter would advance the screen after approximately ten seconds. After twelve presentations, the software displayed a "well done" message together with an animation and sound. No specific feedback was

given to the children during this phase of the trial, although general encouragement and non-specific praise (such as "That's great!") were given to keep the children engaged with the task.

9.6.10 Teaching Phase

The teaching phase comprised a further six presentations of the hybrid condition, featuring both stimuli. During this phase, children were given specific verbal instructions using the principles of causal language described above and were provided with coaching and feedback on their performance. In the eye-control condition, children were told the following:

- That the goal was to look at the effective stimulus until it played a video ("You need to look at the lady to make the video play")
- That the ineffective stimulus would not do anything when looked at ("Nothing happens when you look at the man")
- That the cursor on the screen was being controlled by their eyes ("The red box shows where you are looking")
- That the dwell progress marker must complete in order for the video to play ("You need to look until the circle goes all the way round")

In the touchscreen condition, children were told the following:

- That the goal was to press the effective stimulus ("You need to press the lady to make the video play")
- That the ineffective stimulus would do nothing when pressed ("Nothing happens when you press the man")
- That the screen needed to be pressed until the dwell progress marker had completed for the video to play ("You need to press until the circle goes all the way round")

In both trials, children were given feedback which explicitly reflected back what they had done in order to trigger the video reward, for example: "Well done! You played the video by looking at the lady!", or which made explicit any errors in selection, for example: "Oh dear! Looking at the man doesn't play the video!". In order to keep the protocols for the two access methods as similar as possible, no modelling (such as pointing to the icons or simulating the

pressing of the screen) was used during the touchscreen teaching exercise. After the teaching phase, children were given a short break of up to one minute, during which they were allowed to play with a toy or chat with the researcher or a familiar adult. Since children involved in this phase of the study were all developing typically, it was assumed that there would be no problems with their retaining the information learned in the intervention phase over this short time period.

9.6.11 Post-Intervention Testing Phase

The final phase of the trial repeated the procedures outlined in the baseline hybrid phase, with the effective and ineffective buttons appearing on screen together for a further twelve trials. Once again, no specific feedback was given to the children, although they were given praise and general encouragement.

At the end of the experiments, children were given a sticker as a reward for participating and were thanked for taking part.

9.6.12 Scoring and Recording

A score sheet was used to record the number of selections of the effective icon in both the baseline and post-intervention testing phases. A copy of the score sheet is included in Appendix D-4. This sheet recorded whether children had selected the effective or ineffective icon and provided space for observations and notes to be recorded. To better elucidate the nature of children's engagement when they failed to select the effective stimulus, a coding system was derived. For each trial, children's attempts were allocated to one of five categories:

1. Successful selection
2. Unsuccessful - no attempt at selection made within 10 seconds
3. Unsuccessful - selection of ineffective icon
4. Unsuccessful - selection of another (blank) area of the screen
5. Unsuccessful - attempt to touch the screen (applicable only for the eye-gaze condition)

All sessions were recorded by a video camera which was focused on the screen of the device. Videos were used to validate the scoring of trials to ensure accuracy and to make further observations on the reasons why trials were not successful. Video recordings were also reviewed to code unsuccessful trials as described in the Results section.

9.6.13 Analysis

Quantitative data collected during the study were analysed using IBM SPSS statistical analysis software (v 26.0.0). The data were analysed to investigate the following:

- Relationship between age and performance in both touchscreen and eye-gaze tasks
- Whether the order in which the access methods were used had any impact on performance
- How children's performance on the task using eye-gaze compared with their performance using touchscreen
- Whether causal language instruction had any impact on children's performance
- Whether any increase in performance after teaching was retained when the modelling and prompting were withdrawn
- The reasons for any unsuccessful trials

9.7 Results

The qualitative observations made during the study and the results from the above analysis are presented below.

9.7.1 Cause and Effect with Physical Objects

All children taking part in the study were able to use the toy in the initial play-based assessment as described above and therefore demonstrate understanding of cause and effect with real objects.

9.7.2 Attrition and Groupings

Children were invited to attempt one of the access tasks. At this stage, four children (M_{age} = 26.25, SD = 6.13) did not take part and could not be persuaded to engage with the activity. Review of the field notes revealed that these children either refused to cooperate or requested instead to play with something else. One further child (29 months) completed the

eye-gaze task, but then refused to take part in the comparison touchscreen task. This child's data was therefore also excluded from subsequent analysis. The final group who are included in this study (n = 9; 3 male, 6 female) had an age range of between 24 and 35 months (M_{age} = 28.67, SD = 4.82).

The remaining children were allocated to one of two groups: (A) touchscreen-eye-gaze and (B) eye-gaze-touchscreen. An independent-samples t-Test was conducted to determine if there was any difference in age between the two groups. There were no outliers in the data, as assessed by inspection of boxplots (Figure 44). Ages were normally distributed as assessed by Shapiro-Wilk's test (p > .05). There was homogeneity of variances, as assessed by Levene's test for equality of variances (p = .953). This test indicated that the groups were evenly matched for age ($t(7)$ = .043, p = .967), with no significant different between group A (n = 4, M_{age} = 28.75, SD = 5.19) and group B (n = 5, M_{age} = 28.60, SD = 5.13).
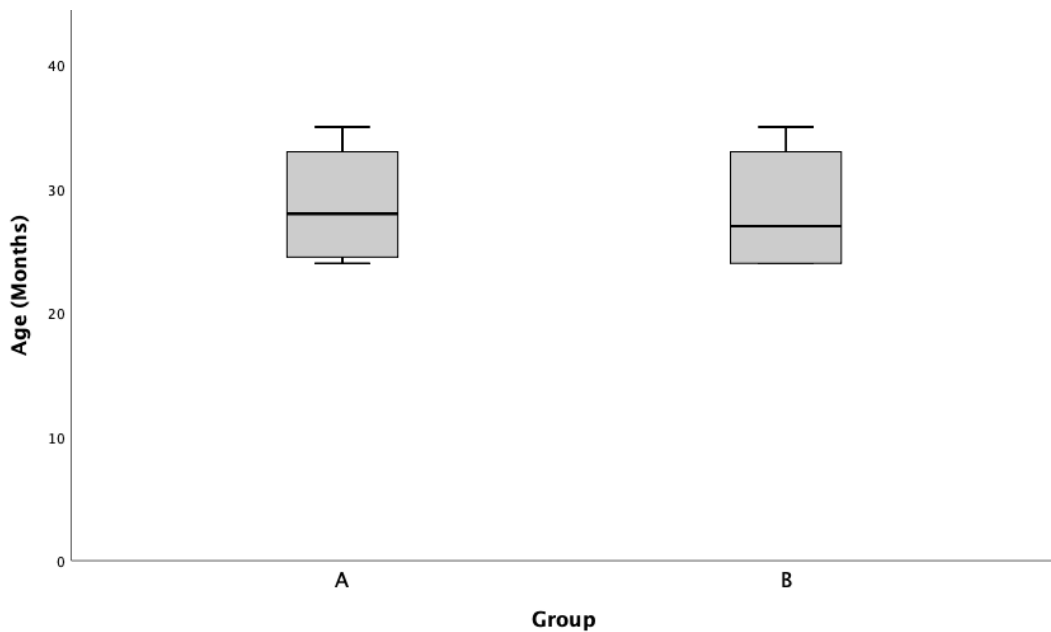
Figure 44 - Graph showing equal distribution of age between the two groups
(A) Touchscreen-eye-gaze and (B) Eye-gaze-touchscreen

9.7.3 Order of Presentation

As discussed above, the two groups of children were counterbalanced and presented with the two access methods in different orders. To investigate whether an order effect was present, a two-way mixed design analysis of variance (ANOVA) was conducted. This test was conducted with one within-subject factor (access method), four levels (eye-gaze baseline,

eye-gaze post intervention, touchscreen baseline and touchscreen post-intervention) and one between-subjects factor (order of presentation: A or B).

The Shapiro-Wilk Test for normality was conducted on all data, with three of the levels being normally distributed ($p < .05$) and the data for touchscreen baseline being non-normally distributed ($p = .024$). However, due to the small number of participants, the ANOVA was continued. No outliers were identified on review of box plots. Homogeneity of variance assumptions were met for all levels as shown by the Levene's score ($p > 0.05$).

The mixed ANOVA confirmed that the counterbalancing of groups was successful, with no difference in performance observed between the orders in which the two access methods were presented ($F(1, 7) = .26$, $p = .628$).

9.7.4 Relationship between age and performance

Pearson's correlation calculations were carried out to assess the relationship between age and performance on the touchscreen task, age and performance on the eye-gaze task, and age and overall performance. Preliminary analyses showed the relationships to be linear with all variables being normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$). No outliers were identified in the data on review of box plots. Homogeneity of variance assumptions were met, shown by the Levene's score ($p > .05$).

Correlational analysis showed no significant correlations between age and performance on the touchscreen task ($r = -.002$, $p = .997$), age and performance on the eye-gaze task ($r = .12$, $p = .754$), or age and overall performance ($r = .75$, $p = .125$).

9.7.5 Performance on Touchscreen and Eye-Gaze

The average number and percentage of successful trials (where a successful trial is one in which the effective icon is selected) for all children included in the study ($n = 9$) across the three phases with two access methods are summarised in Table 7.

A two-way repeated measures ANOVA was conducted with two within-subject factors: testing phase (baseline or post-intervention) and access method (touchscreen or eye-gaze). Normality assumptions for all levels were checked using the Shapiro-Wilk test and were met

(p > .05) for three out of the four levels; the exception being post-intervention touchscreen data (p = .026). Once again, the ANOVA was conducted due to the normality assumptions being met in all other levels and the relatively small numbers involved in the calculations. No outliers were identified on review of box plots. Homogeneity of variance assumptions were met at all levels as shown by the Levene's score (p > 0.05).

Table 7 - Average number & percentage of successful trials for touchscreen and eye-gaze access trials

	Baseline (12 Trials)			Intervention (6 Trials)			Post-Intervention (12 Trials)		
	$M_{success}$ (n)	$M_{success}$ (%)	SD	$M_{success}$ (n)	$M_{success}$ (%)	SD	$M_{success}$ (n)	$M_{success}$ (%)	SD
Touchscreen	9	75%	2.69	5.67	94.59%	0.71	8.88	74%	3.33
Eye-Gaze	5.11	42.58%	3.33	5.44	90.67%	1.01	4.33	36.08%	2.50

The results indicated that there was no significant main effect of testing phase and access method ($F(1, 8)$ = .36, p = .563), nor of testing phase independently ($F(1, 8)$ = .49, p = .505). A significant main effect of access method was however observed ($F(1, 8)$ = 8.42, p = .02, ηp^2 = .51) with the partial eta squared indicating a large effect size.

Taken together, these results indicate that the causal language intervention did not have a significant effect on children's performance, but that the children in the group did make significantly more correct selections on touchscreen ($M_{success}$ = 8.94, SEM = .84) than eye-gaze ($M_{success}$ = 4.67, SEM = .87) across both the baseline and post-intervention phases.

9.7.6 Impact of Teaching Intervention

The data in Table 7 shows that there was variation in performance across the trial phases, with greatest success for both access methods in the intervention phase, where the majority of trials were successful. During the intervention phase 94.59% of touchscreen trials and 90.70% of eye-gaze trials were successful. Both of these represented an increase in performance, however the increase in performance with eye-gaze was far greater, as shown in Figure 45. An extension of the above ANOVA calculation to include the intervention phase indicated that there was a significant increase ($F(2,16)$ = 30.2, p = <.001) in mean percentage of correct responses using the eye-gaze system in the intervention ($M_{success}$ = 42.6%, SD =

27.8) as opposed to the baseline phase ($M_{success}$ = 90.7%, SD = 16.9), a mean increase of 48.2% (95% CI, 24.5% - 71.8%).
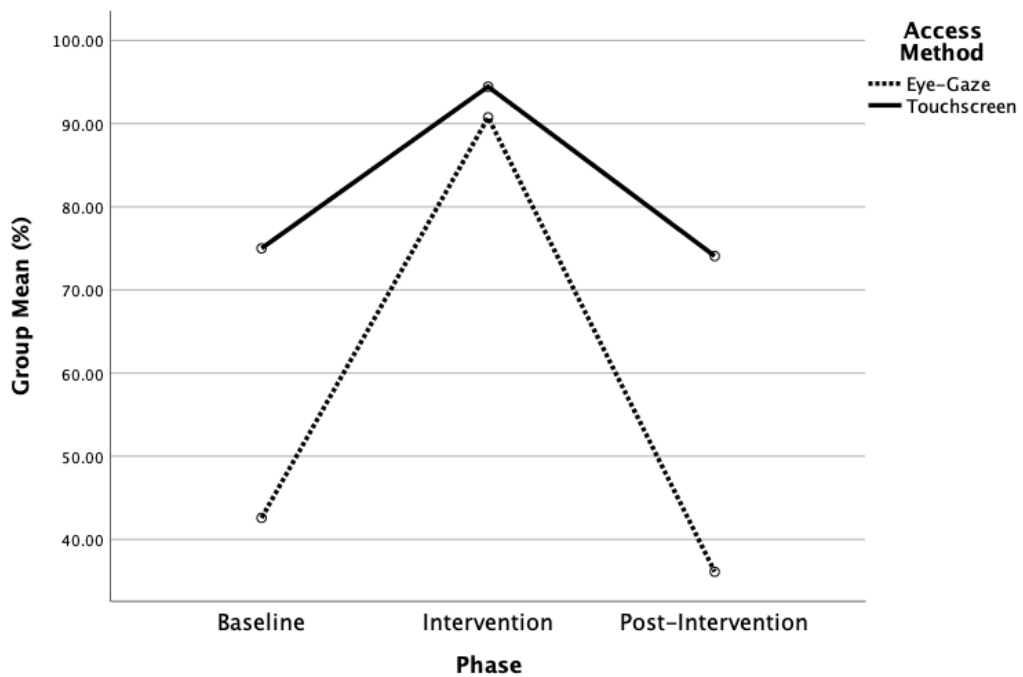
Figure 45 - Graph showing the change in group performance (percentage of correct trials) across the three phases of the experiment

Both the baseline and post-intervention phases had comparatively low success rates, with children regressing to below their baseline scores for both access methods. This may indicate that explicit instruction, teaching and modelling had an immediate effect, but that this effect was not retained once the supports were removed.

9.7.7 Unsuccessful Trials

Trials in the baseline and post-intervention phases where the effective icon was not selected were coded retrospectively using the video recordings. After reviewing the recordings, the reasons for unsuccessful activations were coded into one of the five groups outlined in Section 9.6.12 above. These were not recorded for the intervention phase, since children averaged less than one error each on either access method during this part of the experiment. A summary of the reasons for which a trial was deemed unsuccessful are recorded in Table 8.

Table 8 - Reasons for unsuccessful trials (total across all children)

	Baseline Phase				Post-Intervention Phase			
	No Selection	Ineffective Icon	Blank Area	Touching Screen	No Selection	Ineffective Icon	Blank Area	Touching Screen
Touchscreen	2	22	3		9	14	5	
Eye-Gaze	6	23	9	24	11	33	7	18

The high number of times children attempted to touch the screen during the eye-gaze trials may be indicative of their increased familiarity with touchscreen technology in their day to day lives, as previously discussed, or may be related to a preference for the spatially contiguous nature of a touchscreen. It is noteworthy that children selected the ineffective icon more often in the post-intervention phase when using eye-gaze technology.

9.8 Discussion

This section of the thesis looked at the impact of teaching on the performance of typically developing pre-schoolers using eye-gaze technology. The experiments also examined the difference in performance between two different access methods: eye-gaze and touchscreen technology.

Before embarking on a discussion of the results and their implications, it is worth reviewing the impact of the changes to the experiment design. The group of children completing the full experimental protocol in this chapter (M_{age} = 28.67, SD = 4.82, $Range$ = 25 - 35) were younger on average than those in either the first or second experimental chapters, suggesting that the redesign had enabled some younger children to engage with the activity. This experimental protocol made several changes to those used previously. Importantly for the potential use of similar experiments in children with cerebral palsy (CP), the change in stimulus design to include human faces did appear to allow younger children to engage with the task. Locating the reward video at the same onscreen location as the stimulus appeared to better foreground the link between cause and effect and the use of additional feedback and snapping did not provide a level of support that invalidated the results. In line with the results of the previous two experiments, however, children below 24 months of age did not engage in the activity.

The lack of a significant relationship between increasing age and performance in the group who did engage with the activities may indicate that the redesign of the experiments over the past three chapters has now resulted in an activity in which a broader age range of children can participate equally. The addition of the touchscreen condition has demonstrated that all children participating in this phase of the study, regardless of age, understood the concept and goals of the activity. This therefore allows for closer examination of the difficulties controlling the eye-gaze system.

Returning to the research questions for this chapter:

1. Can typically developing pre-school children learn to better use eye-gaze control technology after explicit teaching and instruction using causal language?

2. Do typically developing pre-school children perform better in cause and effect tasks when using touchscreen technology than when using eye-gaze control technology?

3. Will the likely performance disparity between performance on touchscreen and eye-gaze control tasks decrease after explicit teaching and instruction?

Taken as a whole, the results from this experiment support those from the previous two chapters in indicating that there are different and / or greater challenges in the learning and application of cause and effect skills within the context of eye-gaze technology use. This experiment adds to this discussion firstly by confirming that all children were able to demonstrate understanding of cause and effect using physical objects and secondly by comparing their performance with eye-gaze against the same activity administered via a touchscreen. Since all children who participated in this study were able to show evidence of established cause and effect skills and better performance when using the touchscreen, it is now more likely that there is something specific to eye-gaze technology itself that these children find challenging. The consistently high occurrence of children pressing the screen during the eye-gaze condition, even when this was deactivated and had no effect, points towards these difficulties being related to the non-spatially contiguous nature of the cause and effect relationship.

Parallels for this finding could be drawn from elsewhere in the published literature. Kushnir and Gopnik, for example, demonstrated that children prioritise spatially contiguous cause and effect relationships when exposed to new toys. In their experiment, when children were given a musical toy that activated when an item was either placed on it or held over it with no contact, they showed an overwhelming preference for contact as a method of activation when first exploring the toy (Kushnir & Gopnik, 2007). Further, the same researchers demonstrated an association with age that may help to place these findings in a broader context. They conducted an additional experiment where the method of activation ("on" or "over") was shown to children in two different age groups (average age of 38 and 47 months), before they were asked to apply this learned knowledge to activate the toy themselves. All children shown the "on" condition were able to replicate this, regardless of age group. However, younger children in the "over" condition replicated what they had seen only at the level of chance (59%) compared to the older group, the majority of whom (79%) were able to apply correctly what they had seen. The authors of that study concluded that older children were better able to learn and apply new causal information, despite the fact that they had no knowledge of the causal mechanism and that the relationship was non-contiguous. Contrasting this with the younger children's results, they reasoned that younger children appeared to have an inbuilt bias or preference for spatially contiguous cause and effect. These children, the researchers reported, had more difficulty overriding their prior preference for contiguity in the face of new evidence. Other experiments by the same authors and their associates demonstrated that 4-year-old children are consistently over-ride spatial contiguity when presented with new information that a causal relationship is non-contiguous (Bonawitz et al., 2010; Gopnik et al., 2004; Kushnir & Gopnik, 2007; Sobel & Kirkham, 2006).

The findings of the current experiments would seem to be in line with those described above. Since all children included in this study were below the age of even the younger group, it may be that the non-spatially contiguous nature of eye-gaze is the cause of their difficulty. The finding that these children are better able to complete this activity with a spatially contiguous access method that provides more feedback (touchscreen) would support this. However, the final sample size in this section of the study (*n* = 9) is small, and therefore the results may not be generalisable to all children in this age bracket and should be interpreted with caution.

The first research question addressed in this chapter, that of whether a causal language intervention could improve the performance of children on an eye-gaze task requires an answer in two parts. From the observations made here, it would appear that the intervention itself had an impact on performance during the intervention phase, increasing children's performance. This was evident for both the eye-gaze and touchscreen conditions but was particularly the case for eye-gaze technology where, with explicit instruction, children's performance improved significantly. Whether this is due to causal language specifically is currently unclear. This increase in performance may be indicative of a general improvement in engagement with tasks when an adult is attending to the same task and offering support and greater encouragement. This finding suggests that the instruction given to children did have an immediate effect on their performance during the teaching session, but it also adds further weight to the idea that eye-gaze technology is not intuitive for younger children, since their performance only approached that of a more familiar and more intuitive access method with the additional support of proactive teaching.

However, it was observed that children in this study were not able to retain the performance increases from the intervention phase of the study to the post-intervention phase. This is particularly interesting given the short time between the intervention and post-intervention phases. The assumption that children would retain the information from the intervention to the post-intervention phase was not proved correct. Rather, children's performance returned to a level similar to the baseline phase. For the eye-gaze condition, the number of errors and the different types of these were reasonably similar between the baseline and post-intervention phases. This addresses the third research question by showing that teaching did have an immediate impact on performance and did indeed increase levels of performance with eye-gaze to levels similar to those observed with a touchscreen. However, this improvement was not retained.

In summary, then, whilst this group of children could perform to a high level with the eye-gaze device, they did not do this either intuitively or independently and causal language intervention did not result in consolidated performance increases.

The second research question, that of whether children would perform better with a touchscreen than with the eye-gaze system, has a much clearer answer: children performed

consistently better with the touchscreen across all three phases of the experiment. The modification of the touchscreen to include a delayed activation makes it less likely that children's performance with this access method is solely attributable to pre-existing familiarity with the technology, although it would be logical to assume that this familiarity played a part, with children already being familiar with the "tools" used to tackle the problem of how the touchscreen functioned.

9.9 Implications for Future Work

The experimental work conducted so far seems to show that, whilst children as young as 25 months can engage with eye-gaze tasks, older children (32 months and above) appear to be at a developmental advantage when first acquiring the skills needed to make purposeful use of eye-gaze technology. Younger children show more difficulties with engagement and do not seem to be as able to learn the causal relationship between eye movements and resulting actions on the device.

Crucially, all children recruited to this phase of the study were at a language and cognitive level where they would be expected to understand the causal language used by the researcher. This may not be the case for many children with CP who are considered for eye-gaze technology. This raises a question about what could be learned by children who may be unable to make the causal link between moving their eyes and controlling the computer through using error-free activities, if they are similarly unable to understand the verbal instructions given to them by the researcher.

9.10 Conclusion

Having refined the design and implementation of the experiments over three consecutive phases with typically developing children, the final section of this thesis takes this final experimental protocol and applies it to a group of children with cerebral palsy (CP). This will allow exploration of whether what has been learned from the group of typically developing children also applies to children with CP. However, as alluded to in the introductory chapters of this thesis, children with CP are at greater risk of impairments of vision, attention, cognition or language understanding. Returning to the guiding principles of the Matching Person and Technology (MPT) model at this stage, it seems important that these experiments

are supplemented by measures that allow greater understanding of a child's profile of strengths and needs.

Therefore, the following chapters discuss the importance of measuring one particular construct that is likely to have particular relevance to the use of eye-gaze technology: functional vision.

Chapter 10

Functional Vision and Functional Gaze Control

10.1 Introduction

Whilst the studies reported in this thesis so far have given insight into some of the developmental aspects of making use of eye-gaze control technology, these studies have focused on cohorts of typically developing children without motor impairments and who have no sensory or cognitive impairment. This chapter of the thesis returns the focus to the clinical population of children with cerebral palsy (CP). As outlined in the background section of this thesis, children with CP may present with a range of co-occurring impairments, including those of motor, cognitive and sensory functions. As previously highlighted, this group of children are at an increased risk of disorders of all aspects of the visual system.

When a child's motor impairments preclude the use of accurate and sustained finger-pointing, the use of directed gaze can play a significant role as a communication and response modality (Sargent et al., 2013). However some studies have suggested that there is a tendency among clinicians to over-ascribe intentionality to children using looking behaviours, in both clinical assessment (Sargent et al., 2013; Schietecatte et al., 2012) and behavioural observation (Carter & Iacono, 2002). Further, it has been suggested that use of looking behaviours, sometimes called "gaze pointing" or "eye pointing" may be a less robust response modality than others such as finger-pointing (Kurmaviciute & Stadskleiv, 2017) as there is often an element of interpretation of the direction of gaze, or the length of time which constitutes a purposeful selection, by the parent, clinician or researcher when conducted through observational paradigms alone (Geytenbeek et al., 2010). Thus, the use of vision as a response modality in assessment or as a method of choice-making continues to be the subject of much debate.

10.2 Defining Functional Vision

A recent review article by Deramore Denver and colleagues (Deramore Denver et al., 2016) draws attention to an important distinction in reporting the vision of children with CP. This is the distinction that exists between "visual impairment", which refers to disorders of the eye, ocular-motor systems or cortical visual systems (including refractive errors, myopia,

hypermetropia, astigmatism and strabismus) and "visual ability", which describes how a child with CP functions in vision-related activities (Colenbrander, 2003). The authors of this review cite the *International Classification of Functioning, Disability and Health* (ICF) framework as one appropriate to define and describe the measurement of vision. In this framework, "visual impairment" or "visual function" is aligned with the Body Functions and Structures domain – encompassing as it does the physiological and mental or cognitive processes involved in the movement of the eyes and the processing of visual information. The authors highlight that assessment of vision is often focused on this domain, with measures of visual acuity, visual fields, light sensitivity etc. being readily available to clinicians. The authors propose that, since measurement of visual impairment does not directly provide information on functional performance in daily life, a second construct known as "visual ability" or "functional vision" is needed to describe how an individual makes use of their vision. It is proposed that functional vision is therefore better captured by codes in the Activity ("the execution of a task or action by an individual" (World Health Organisation, 2001a)) and Participation ("involvement in a life situation" (World Health Organisation, 2001a)) domains of the ICF, since it describes the performance in vision related tasks (Deramore Denver et al., 2016). Colenbrander draws a similar distinction, again using the ICF as a basis, suggesting that in order to have a complete understanding of a person's vision it is necessary to understand the structure of the eye, how well it functions, the resulting impact of those on the person's abilities to perform an activity and the broader impact of that performance on the person's quality of life and participation at a societal level (Colenbrander, 2003, 2010).

In essence, functional vision can therefore be thought of as "vision for doing" or "vision used to perform critical or meaningful tasks" (Hall Lueck, 2004) and describes the qualitative observations and description of the functions of a child's vision: what it is that a child does with their vision as a function of their ocular-motor and related visual systems.

When making use of any intervention for children with CP, careful assessment and consideration of both visual impairment and visual ability are therefore recommended (Jones et al., 1990; Sargent et al., 2013). This is particularly important when children may be expected to use their vision to make selections or signal choices, and even more so when considering the provision of AAC or any adapted computer system for learning, play or leisure. Just as knowledge and awareness of a child's visual acuity will inform decisions about

the size of onscreen items and assessment of a child's visual field will be helpful in determining the placement of resources, so observations of what a child is doing with their vision can provide insight into their understanding of the activity and help provide better descriptions of children's functional performance.

Functional vision requires the intentional use of "functional gaze control" skills, which include gaze fixation, gaze switching, visual searching and tracking moving objects. These skills are the core requirements which underpin the purposeful, directed use of gaze to signal messages, control a computer or to give responses in assessment. Applying these skills incorporates also the inhibition of other eye movements, the maintenance of focused attention, and, where required, linking head movements with gaze shifts. Since these skills require the employment and coordination of a range of different regions of the brain, they are considered to be particularly vulnerable to damage in conditions such as CP (Luna et al., 2008) and it has been suggested that understanding and observations of these skills can provide some insight into general developmental delay, neurological status, and prognosis (Atkinson, Anker, Rae, Hughes, & Braddick, 2002).

The following section discusses what is known about the development of these core skills. This section does not discuss the development of smooth pursuit or "visual tracking", since it is not directly relevant to the activities in this thesis. For a comprehensive description of the development of this skill, the reader is directed to papers by Fukushima and colleagues, and Luna and colleagues (Fukushima, Akao, Kurkin, Kaneko, & Fukushima, 2006; Luna et al., 2008).

10.3 Development of Functional Gaze Control

In typical development, functional gaze control skills develop early and quickly, such that children can demonstrate them functionally by the age of 12 months (McCulloch et al., 2007), although most continue to develop and become more finely tuned throughout childhood and into adolescence (Luna et al., 2008). The fundamental status of these skills as indicators of basic visual functioning has made them standard elements of ophthalmological examination and they are also incorporated into established inventories of visual functioning (Ferziger et al., 2011; McCulloch et al., 2007). In child development, for example, noting that an infant has poorly sustained fixation or difficulties shifting gaze may be the first sign of problems

with visual development or a possible indicator of a number of neurological or neurodevelopmental disorders and should prompt clinicians to undertake further, more specialist assessment (Sharma et al., 2014; Sonksen, 1993).

10.3.1 Gaze Fixation

The fixation of gaze can be described as the voluntary and deliberate process of stabilising the fovea on a stationary target, with the inhibition of other eye movements. Crucially, this is not a passive process of "resting" the gaze, but the active stabilising and maintenance of the fovea on a target (Luna et al., 2008) while inhibiting other eye movements and other things in the visual field. Fixation is used primarily to take in information about the target of gaze and is considered to be a key indicator of a person's attention. In vision science and neuroscience, analysis of fixations may provide important diagnostic information for the identification of disorders (Hansen & Ji, 2010). Absent fixations might prompt a clinician to consider whether full assessment of a child's vision is required, as this may be an indicator of an underlying visual impairment.

It should be noted in this discussion that the use of the term "fixation" in the behavioural observation of gaze is distinct from the meaning it has in discussions of eye tracking research. In eye tracking, fixation is generally defined as a cluster of recorded gaze points located spatially and temporally close together (Wilkinson & Mitchell, 2014). Such fixations are generally recorded to analyse how a person takes in visual information, to look at the order in which they attend to things in their environment or to assess how much time is needed to process information when it is presented (Eckstein, Guerra-Carrillo, Miller Singley, & Bunge, 2017). The spatial and temporal threshold for fixations can be defined by the researchers conducting the experiments but tend to be very brief. Typically, fixations last 200 – 300 ms (K. Holmqvist et al., 2011) meaning that around three fixations can take place per second (Henderson, 2003), although some researchers place the threshold as low as 80 ms in order to gather richer data on the way in which visual information is being acquired and processed (Hansen & Ji, 2010; Wass, Smith, & Johnson, 2013). Clearly, there would be difficulties observing this behaviourally without the aid of eye-tracking equipment. Therefore, behavioural observations of fixation tend to use the term to refer to the observed, steady holding of the gaze on one particular object or area. In these studies, the threshold for fixation is often much higher – frequently multiple seconds (Fleming et al., 2010) – in order

to give the observer confidence that the fixation is purposeful and controlled (Deramore Denver et al., 2017; Sargent et al., 2013).

Typically developing newborns show some tendency to fixate on highly salient patterns or objects (Braddick & Atkinson, 2011) and particularly on faces (Chawarska et al., 2010), although these need to be brought into close proximity (≤30cm) to obtain a fixation (Sharma et al., 2014). Since these fixations tend to be lengthy (up to 60 seconds), it has been suggested that the newborn has not yet developed enough purposeful control of their visual system to gather much information from these "rests" and that they therefore may not constitute true fixation as defined above. Voluntary control over fixations is considered to emerge between three and six months (Atkinson et al., 1992; Braddick & Atkinson, 2011) at a similar time to the coordination of eye and head movements to explore the environment. Studies have shown that the duration of fixations is linked to development, with older children showing longer fixations with fewer "breaks".

Sargent and colleagues describe two important functions of fixation for the typically developing infant. Firstly, it is the means through which an infant attends to objects and persons in their world; and secondly, it is the means through which the target of interest is made evident to others (Sargent et al., 2013), although this interest has to be "read" by a partner since the infant cannot yet signal that this is the function of their fixation on an object. Whilst typically developing infants begin to replace this second function with finger pointing at around one year of age (see Section 3.1.4), many children with CP whose motor skills are more severely impaired are unable to use their hands in this way and fixations on objects can continue to play a vital role in their wants and needs (M. Clarke et al., 2016). In eye-gaze technology fixations form the basis of dwelling to make a selection and are also used to take in information about what is displayed on the screen. Consolidated ability to fixate can therefore be reasonably assumed to be fundamental to purposeful control of an eye-gaze system.

10.3.3 Gaze Switching

Gaze switching or "gaze transfer" is the deliberate process of disengaging fixation from one object and transferring it to another. Researchers class this behaviour as a visually guided saccade – where the gaze is shifted from an initial target in response to new or novel visual

information (Fischer, Biscaldi, & Gezeck, 1997; Luna et al., 2008). From a research perspective, understanding how children switch their gaze between objects has value not just in terms of looking at their functional use of vision. Researchers have demonstrated links between increased latency of visually guided saccades and features of autism, for example (Elsabbagh et al., 2009) and have noted correlations between slowed reaction times, poorer switching accuracy and intellectual disability (Boot, Pel, Evenhuis, & van der Steen, 2012; Boot, Pel, Vermaak, van der Steen, & Evenhuis, 2012).

Studies have shown that this behaviour again develops early in life. Under optimum conditions (switching between two highly salient targets which are not visible together, with no auditory or visual distractors in the visual field) children can demonstrate this behaviour in the first month of life (Atkinson et al., 1992), but the switching is often slower and relatively inaccurate. The ability to switch gaze between two objects develops rapidly thereafter and by three months of age, typically developing infants are able to switch their gaze more accurately and with greater contrast detection. Infants at three months are also increasingly able to cope with the presence of "competition" – where the central stimulus remains in place and requires the infant to actively disengage their fixation to switch to another (Atkinson et al., 1992). Thus, gaze switching is made up of two related parts: disengagement from the current object of focus and transfer of gaze to a fixation on something else.

Once again, gaze switching plays an important role for children with CP who may be expected to use their eyes to signal messages. The ability to switch gaze between objects or choices proffered by a communication partner is important in showing to the communication partner that all available options have been taken in before a response is made. Similarly, adding a social component, the ability to switch gaze from an object to the communication partner and back again can provide increased confidence for the receiver of the message that the choice being made is purposeful.

In eye-gaze technology, gaze switching is a key component of a child's being able to move their eyes around the screen and switching attention between onscreen items. When considered in the context of the activities developed in this thesis so far, the ability to switch gaze between items could be seen as a prerequisite to completing the activity.

10.4 Functional Gaze Control in Cerebral Palsy

It is well established (see Chapter 4) that children with severe CP affecting the whole body are particularly vulnerable to damage to diverse aspects of the visual system. As alluded to previously, since the areas involved in the deployment of functional gaze control skills such as fixation and gaze switching are distributed throughout the brain, these skills are vulnerable to being damaged or poorly developed in this group.

This presents a difficulty for those working with this group of children. As has been discussed in the early parts of this thesis, where children are not able to affect an accurate point with any single part of the body, the use of gaze as a response modality can assume great importance (M. Clarke et al., 2016). For many children with motor impairments, the first steps in using an AAC system may be the use of directed gaze or "eye-pointing" to make choices from a selection set of symbols or real objects (M. Clarke et al., 2016; Sargent et al., 2013), which is often considered a direct substitute for finger pointing. As has already been shown, making effective use of eye-pointing requires the use of the functional gaze control skills described above. Where these skills are sufficiently developed, children may make use of them to make requests or to signal choices from an array on offer. Clarke and colleagues point out:

For many children with CP, AAC symbol displays are first accessed by directing gaze toward and attending to a symbol array. In identifying a target symbol, children are required to fix gaze, to disengage and transfer gaze in order to search and to selectively attend to specific items. Children with cerebral palsy require careful assessment of these functional gaze control abilities. Failing to appreciate the extent of performance of this core skill set will significantly hamper the development of carefully focused and individualised intervention.

(M. Clarke et al., 2016, p. 375)

10.5 Assessment of Functional Gaze Control

Measurement of functional visual ability is seen as a complex process. This feeling is due in part to the perception that all aspects of vision are the domain of specialist vision professionals (Sargent, J., personal correspondence) and require extensive training or experience. This is a misunderstanding, however. Returning to the review by Deramore Denver and colleagues (2016), the authors invite their readers to contrast assessment of visual acuity – where precise quantitative measurements are made and compared, often

requiring a battery of tests and specialist equipment – with the task of providing qualitative observations of how vision is used in everyday life (Deramore Denver et al., 2016). It is possible, several authors have proposed to assess the key functional gaze control skills of fixation, gaze switching and smooth pursuit without the need for any specialist equipment or knowledge (M. Clarke et al., 2020, submitted for publication; Colenbrander, 2010; Ferziger et al., 2011).

Elicitation of fixation, for example, is part of early developmental vision screenings, where children's fixation on a small object such as a ball is frequently used to test this skill (Sharma et al., 2008; Sonksen, 1993). The use of tasks such as these is specifically designed to reduce the social, cognitive and language demands placed on the child (Wallis et al., 2013), ensuring that the functional gaze control skills are the ones being tested. However, these skills can often be observed and documented in the context of other formal or informal assessments. Consider, for example, a basic choice-making or labelling task, when the child is asked to identify one object from a choice of two. In order to complete this task, the child would need to at least demonstrate fixation and gaze transfer between the two objects.

Despite their importance, functional vision skills are often under-reported by professionals working with children with CP. The value of assessing children's functional gaze control skills is underlined by Sargent and colleagues (Sargent et al., 2017). In this study, 35 children with CP who were referred to a specialist communication clinic were reviewed, and each was given a full functional vision assessment. All 35 children were described as using "eye-pointing" for communication in some form, but none had had any structured assessment of their functional vision skills prior to referral. Referring therapists for 12 children reported that they had noticed limitations in functional use of vision for communication and assessment matched reported skills in all cases. However, referrers reported positive functional use of vision for communication in 19 children, but assessment disagreed in 18 cases. The sensitivity of referrer reported limitations in functional use of vision for communication was only 39%. Four children described as using eye pointing or look choosing were using reach as a response method.

10.5.1 Assessment of Functional Gaze Control using Eye Tracking Technology

Eye tracking technology appears to offer unique possibilities in the investigation of functional gaze control skills in children with CP and other developmental disorders such as learning difficulties and autism. Venker and Kover (2015) propose that these methods are ideal for studying children with neurodevelopmental disorders, since "they have the potential to provide information about complex cognitive processes simply by measuring where an individual looks at specified moments in time" (Venker & Kover, 2015, p. 1179). Eye tracking has the potential to provide "real-time" feedback on a user's eye movements, allowing exploration of the ways in which children with disabilities process information, rather than relying on inference from responses that take place after processing has occurred, such as a point or button press.

Several studies have used the technology successfully to measure visual responses (Pel et al., 2016), fixations (Wilkinson & Mitchell, 2014), smooth pursuit (Fukushima, Tanaka, Williams, & Fukushima, 2005) and gaze switching (Hutton, 2008) in newborns, infants and children with a variety of disabilities. The potential advantages of the technology are clear – it offers a way to present stimuli and to capture reflexive or deliberate visual responses without the need for the subject to understand and follow instructions.

As such techniques do not require targeted movements (for example pressing a switch or pointing to a picture) it has been proposed that children with more severe physical impairment could participate in tasks using this technology (Brady et al., 2014). Additionally, since the tasks rely on reflexive eye movement, they do not require understanding of verbal instruction and can therefore be used with young children or those with intellectual disabilities (Boot, Pel, Vermaak, et al., 2012; Venker & Kover, 2015).

Of interest to this project is the need to distinguish purposeful fixations and gaze shifts from the "random" movements of the eye. As has been observed earlier, fixation is an active process, distinct from merely resting gaze. In a recurrence of the Midas Touch problem (see Chapter 5), an eye tracker or eye-gaze system is not able to differentiate between these. For this reason, some authors have argued that the use of an eye tracker to measure gaze responses requires more than the analysis of raw data and can require detailed, post-hoc,

manual coding or the use of sophisticated algorithms written into the experimental design (Venker & Kover, 2015).

10.6 Conclusions

This discussion of functional gaze control and functional vision skill informs the next stage of enquiry. Given the importance of these skills to children with CP, and the increased likelihood that they will present as disordered in this population, assessment of these skills is clearly an important part of understanding a child's profile. This is particularly the case if children are being considered for eye-gaze technology, where these skills will play an additional role: providing control of a computer or AAC system.

Given the potential for both behavioural and eye tracking methodologies to provide insight into these skills, the following chapter tests both approaches with the target clinical population, in order to examine which method can provide the better insight into children's patterns of functional gaze control skills. It should be reiterated that tests of smooth pursuit were omitted from testing in this thesis since, whilst an important functional vision skill, they have little direct relevance to the tasks nor to the use of AAC systems based on static arrays of symbols. The assessment of fixation and gaze switching is relevant to the tasks, as described above, and the two methods of testing these skills are summarised in the next chapter, the results of which will inform how children are tested for the final group of experiments with the eye-gaze tasks.

Chapter 11

Assessment of Functional Gaze Control Skills in

Children with Cerebral Palsy

11.1 Introduction

The previous chapter summarised current thinking on functional vision in children with cerebral palsy (CP). Since many of the core functional vision skills (fixation, smooth pursuit, gaze switching) represent those which would be required to use eye-gaze technology, understanding the profile of functional vision skills in this group becomes an important part of clinical reasoning when considering eye-gaze as an access method for assistive technology.

This chapter takes the approach that functional gaze skills can be examined by observation of children's eye movements in response to stimuli. The work below compares the utility of both an eye tracker and a behavioural measure in order to investigate how these skills might be best observed in this clinically complex population.

11.1.1 Eye Tracking and Studies of Gaze Responses

In Chapter 2, the distinction was drawn between the eye-gaze systems used for experiments so far and eye trackers. This experiment employs an eye tracker for the first time, which allows for more accurate, passive tracking of the response to stimuli presented. Some researchers have suggested that the use of eye tracking technology may be a useful tool to provide objective and reliable measures of children's looking behaviours (Gredebäck et al., 2010). Studies of children's fixation patterns to provide insight into the development of social orienting (Schietecatte et al., 2012) and false belief (Senju et al., 2010) are found often in the literature on children with autism, for example. Here, the technology is considered well-suited to the task of assessing these children, especially those with more severe cognitive impairment, since it can be combined with assessments that do not require understanding of language and which use children's reflexive orienting or fixation to assess their performance, whilst placing minimal demands on the user (Light & McNaughton, 2014b; Wilkinson & Mitchell, 2014). Questions remain, however, as to the utility of this technology to obtain data from children with CP and other movement disorders. While eye tracking

technology shows great potential to provide greater insight into the skills of this population (M. Clarke, Loganathan, & Swettenham, 2012), research and clinical experience suggests that the higher instance of features known to affect performance in eye tracking tasks may make use more challenging than in populations without physical disability.

One specific issue that arises about the use of this technology with children with CP is the calibration and subsequent accuracy requirements imposed by the technology in order to generate accurate data. As has been previously discussed, accuracy – defined as the distance between the actual gaze location and the recorded x-y gaze point in the eye tracker data – is one of the most important properties of an eye tracker (K. Holmqvist et al., 2011). Accurate calibration is considered so important that most eye tracker software packages will not record data unless a calibration threshold (set by the manufacturer of the camera) is reached. Nyström and colleagues discuss different methods of calibration at length, but invite their readers to consider the calibration task itself; pointing out that a traditional calibration to a number of static points on screen requires the ability to hold a steady fixation and / or sufficient receptive language skills to understand instructions given by a person in control of the device (Nyström et al., 2013). Both of these may be difficult for the target group of children with CP. However, to date, no reliable figures could be identified in the literature for calibration rates in children with CP, despite figures existing for other populations (Light & McNaughton, 2014b). This chapter therefore looks first at whether calibration of an eye tracker is possible for children with CP and what information can be gathered about their functional gaze control skills where a calibration can be achieved.

11.1.2 Behavioural Observation of Functional Gaze Control

Another method for observing children's functional gaze control skills is the use of behavioural testing using "real world" stimuli to elicit gaze responses. Several formal assessments of childhood vision include measures intended to prompt children to fix on objects, to track moving objects and to move their gaze from one object to another. Despite this inclusion in early routine assessment, clinical experience and evaluation suggests that these skills are not regularly reported in children considered for the provision of eye-gaze technology (Sargent et al., 2017). This chapter therefore discusses the use of behavioural methods for observing the functional vision skills of children with CP and describes the development and results of a novel behavioural observation measure. The results of this

measure and the practicalities of its implementation are compared against the use of an eye tracker and the discussion of Whether or not such a simple series of observations might provide helpful insight into the functional gaze profiles of these children is also discussed.

The data from the behavioural experiments described in this chapter were collected as part of a separate but complimentary project with which the author was involved. This project, entitled *Functional Gaze Control Skills in Young Children with Cerebral Palsy*, used the same research subjects. The project was run jointly by University College London (UCL), Great Ormond Street Hospital (GOSH) and Barnsley Hospital. Whilst this author's focus was to lead on the collection of data using the eye-tracking system, the author was also involved in data collection and scoring of the behavioural experiments, in collaboration with other researchers. This provided a valuable opportunity to compare the performance of these children on eye-tracking and behavioural measures. The experimental sections of this chapter therefore constitute a secondary analysis of data collected from this project. For the initial analysis, the reader is directed to the Doctoral Degree in Clinical Communication Science thesis of Dr Katherine Price, entitled *Early Social Communication Skills of Children with Cerebral Palsy* (Price, 2017). Acknowledgement is also made to the contribution of Sam Wallis, who acted as Research Assistant on this project and co-ordinated the majority of the data collection.

The behavioural experiments described in this chapter aimed to produce a clinical tool for the systematic observation and reporting of the functional gaze control skills of children with CP. The study aimed to examine the clinical utility, reliability and validity of the assessment procedures in observing the range and quality of children's observed functional gaze control skills. This procedure was deigned to help "non-vision specialists" provide a description of the use of vision in this population. The secondary analysis of the data presented in this chapter aims to compare the results of the functional vision measures administered via the eye-tracking device with those administered using the novel behavioural assessment.

11.2 Experimental Design

This group of experiments adopted a quasi-experimental, cross-sectional design; with participants all undertaking the same series of tasks at a single point in time. In the eye tracking tasks, children were required to carry out a calibration, followed by two measures

of functional gaze control, which were used to examine the variability of these skills in children with CP. Eye tracking measures were designed by the author and administered by the author and a Research Assistant. In the behavioural tasks, the same tasks are replicated using "real world" stimuli. Behavioural measures were designed by the research team with the support of clinicians working in a specialist developmental communication service. The design of all experiments sought to minimise the social, cognitive and language demands of the tasks, making the procedure accessible to a wide range of children. To ensure that children would be able to attempt the experiments in the initial phase of this study, the services of a vision specialist were recruited to ensure that the experiments used were accessible to children with low levels of vision, including those described as having only detection vision. Detection vision is characterised by the ability to detect a single item against a plain backdrop and differs from visual acuity in that it does not require the resolution of adjacent visual targets (Sonksen, 1993). The use of experiments requiring only detection vision allowed for the inclusion of the largest possible number of children, which in turn allowed the researchers to make observations and gather data on a large and varied group of children who are considered to be representative of the clinical populations being considered for trials of eye-gaze control technology.

11.3 Research Questions

The twin research aims addressed in this chapter are an examination of the utility of using research-standard eye tracking technology in the assessment of children with CP and how results obtained using this technology compared to those obtained using behavioural measures. As such, this chapter addresses the following research questions:

1. Are children with cerebral palsy able to calibrate an eye-tracking computer with enough precision to allow the gathering of reliable data on their eye movements?

2. Is an eye tracking computer a useful tool for collecting information on the functional gaze control skills of this group of children?

3. How do the same group of children perform on behavioural functional gaze control tasks?

4. What is the profile of functional gaze control skills in this group of children?

11.4 Methods

The following sections describe the children referred to the study and the results of the background measures used to ensure that children met the inclusion criteria. Subsequent sections then describe each of the experiments and their results in turn.

11.4.1 Recruitment

Children were recruited to the study from special schools in London as well as through a specialist communication clinic based at a hospital in London. Parents of children meeting the inclusion criteria were given an information leaflet (see Appendix F-2) and invited to make contact with the research team if they were interested in enrolling their children. Consent forms (Appendix F-3) were then sent, and children were enrolled onto the study through their parents returning the completed form. Where children were recruited from schools (see Section 11.4.3), school staff were asked to identify children whom they believed to have a language age of 12 months (one key word) and above. Whilst this was checked using the background measures of language understanding, this inclusion criterion was identified in order to remove the possible confounding factor of profound and multiple learning disability.

11.4.2 Ethical Approval

Ethical approval for this section of the study was granted by the ethics committee at Royal Free Hospital, Hampstead (REC Ref 12/LO/1243). A copy of the ethical approval is included in Appendix F-1.

11.4.3 Participants

The group of children recruited to this study represents an opportunity sample, which is consistent with the research design used. Children were proactively recruited as described above. Inclusion criteria were as follows:

- 4-limb (bilateral) CP requiring wheelchair use (GMFCS categories IV and V)
- chronological age 40-160 months

- language understanding / intellectual ability assessed or reported to be within the at 12 - 54 month range
- hearing levels adequate for speech recognition

Children were only excluded from the study if any of the following were noted during the review of their clinical notes:

- Severe or profound sensorineural hearing loss
- Visual acuity loss not due to correctable refractive errors and sufficient to preclude object resolution at 30cm distance
- Confirmed oculomotor dyspraxia
- Untreated or uncontrolled epilepsy

Children were not excluded if they had been given a description of cortical visual impairment (CVI), as a general diagnosis of CVI does not predict functional gaze control ability (J. Sargent, personal communication).

This phase of the study recruited 66 children with cerebral palsy (34 male, 32 female) aged between 40 and 152 months (M_{age} = 91.1 months, SD = 28.59). Participant characteristics of all children referred to the study are summarised in Table 9. Children with all subtypes of CP were included in the study in order to best reflect the broad range of children being trialled clinically with eye-gaze control technology.

Children's functional motor abilities were classified using the *Gross Motor Function Classification System – Expanded and Revised* (GMFCS-ER; Palisano, Rosenbaum, Bartlett, & Livingston, 2007) and the *Manual Ability Classification System* (MACS; Eliasson et al., 2007). These are both discussed in detail in Chapter 4. There is a strong clinical and theoretical rationale for only including children with higher levels of physical disability, since these are the children who are most commonly considered for eye-gaze technology. Where characteristics were not specified by those referring them to the project, expert opinion was sought from a range of clinicians working in the field, with classification being made from video recordings of children.

11.4.4 Rationale for Participant Selection

The group of children recruited to the study represents an opportunity sample. As such, the children recruited present as a heterogeneous population, with a range of different CP descriptions, physical abilities, developmental and medical histories.

Table 9 - Characteristics of participants referred

	Participants	
	n	% of category
Total	66	100.0
Gender		
Male	34	51.5
Female	32	48.5
CP Type		
Dyskinetic	29	43.9
Spastic	4	6.1
Mixed	20	30.3
Unspecified	13	19.7
Reported Visual Issues		
Strabismus	14	21.2
Dysmorphologies (e.g. astigmatism)	1	1.5
Cortical Visual Impairment	2	3.0
GMFCS-ER Level		
III	2	3.0
IV	18	27.3
V	43	65.2
Unspecified	3	4.5
MACS Level		
III	2	3.0
IV	13	19.7
V	28	42.4
Unspecified	23	34.9

Given the clinical motivation for this research and the widely held acknowledgement that CP is a heterogeneous condition, both in aetiology as well as in type and severity of impairment (Bax et al., 2005), the sample collected was considered to reflect the group of children whose skills and difficulties this project seeks to explore. The group also represents the broad range of children who are considered by education and therapy staff to be candidates for trialling eye-gaze access technology, either for the purposes of expanding their play and leisure opportunities, or for control of communication and computer access software.

11.4.5 Background Measures

All children participating in the study (n = 66) completed two background measures to assess their language and non-verbal age equivalents. These background measures were used to check whether children referred met the core inclusion criteria described above. Receptive language was assessed using the adapted version of the *Pre-School Language Scales UK – 4th Edition* (PLS4-UK) (Zimmerman et al., 2009) as described in Chapter 6 (see Appendix A-1). Professionals identifying children for the study were asked if this measure had been administered within the preceding 12 months, the suggested retest period for this assessment. If a child had been tested during this period, the existing scores were obtained by the researchers. Children's non-verbal cognition was assessed using the visual reception scale from the *Mullen Scales of Early Learning* (Mullen, 1995), which assesses cognitive performance independent of language skills. All background measures were recorded using a digital video camera with integrated microphone. The camera was positioned on a small tripod placed on the desk and the recording was focused on capturing the child's responses. All scoring was conducted at the time of testing and, where necessary, checked against video recordings of the sessions. Following these background measures, 39 children were identified as meeting the inclusion criteria. Reasons that children were excluded at this stage were as follows:

- Language and / or cognition fell below the level for inclusion (n = 12)
- Language and / or cognition fell above the level for inclusion (n = 3)
- GMFCS Level III or below (n = 2)
- Refused to participate or too unwell to participate (n = 2)

- Visual impairment considered too severe to detect test materials (*n* = 8)

The remainder of this chapter therefore compares the performance of these 39 children, whose characteristics are summarised in Table 10.

Table 10 - Characteristics of participants meeting inclusion criteria

	Participants	
	n	% of category
Total	39	100.0
Gender		
Male	21	53.8
Female	18	47.2
CP Type		
Dyskinetic	20	51.3
Spastic	2	5.1
Mixed	8	20.5
Unspecified	9	23.1
Reported Visual Issues		
Strabismus	10	25.6
Dysmorphologies (e.g. astigmatism)	1	2.6
GMFCS-ER Level		
IV	15	38.5
V	24	61.5
MACS Level		
III	1	2.6
IV	9	23.1
V	18	46.2
Unspecified	11	28.2

11.4.6 Equipment and Testing Environment

Children were seen either at home, at school or at a dedicated behavioural laboratory space at UCL. Where possible, separate areas were setup for the background measures, eye-tracking task and behavioural tasks. Every effort was made to minimise distractions in the

environment. Each child was assessed for approximately 90 minutes, ideally within one session although multiple sessions were permitted as required. If a child became fatigued, distressed or indicated that they would like to stop, the session was terminated.

11.4.7 Testing Protocol

The following sections describe the methodology and materials used for both the eye tracking and behavioural measures.

Each child recruited to the study attended one session over the course of a morning or afternoon. Children were accompanied by one or both parents throughout the session, or by a familiar adult if they were seen in school. Over the course of the session, all children completed the background measures, followed by the behavioural and eye-gaze functional gaze control assessments. Breaks were provided between each of the tasks to minimise the effects of fatigue. The basic experimental procedure is summarised in Figure 46 below:
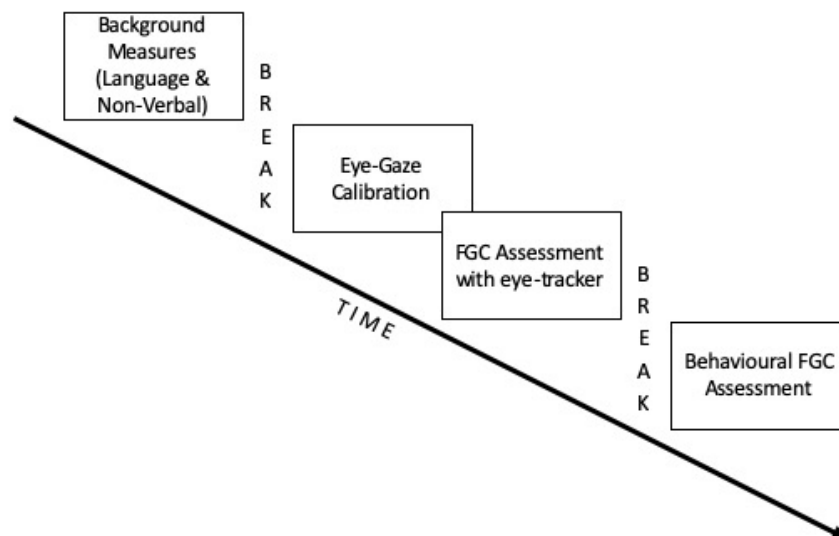
Figure 46 - Schematic diagram of the experimental procedure

11.4.8 Eye Tracking Hardware and Software Setup

For this experiment, an eye tracking system was used. The system selected for these experiments was a *Tobii T60* eye tracking monitor connected to an *HP* laptop running the *Tobii Studio* presentation and analysis software (version 3.2). All stimuli were presented on the T60's 17" monitor (4:3 aspect ratio) with a resolution of 1280 x 1024 pixels. Eye-tracking

data was sampled at 60Hz, meaning that an image of the eye is sampled every 16.6ms. The device also includes a "user camera", which records a live image of the child during the experiments. The recordings from the user camera were used for post-hoc coding and analysis of children who were not able to participate in all tasks.

This system was selected as it has a large trackbox (44 x 22 x 30 cm), allowing for a degree of head movement once a calibration to the users' eyes has been achieved. A large trackbox offers clear advantages in the assessment of children who may have difficulties inhibiting involuntary head movements, such as the population recruited to this study. It has been noted (K. Holmqvist et al., 2011) that data quality varies within the area of the headbox, with the quality of data generally becoming poorer towards the extremes. In order to minimise this as far as possible, children recruited to the project attended in their most supportive seating system. Parents were asked to gently support the child's head during calibration if a large amount of involuntary movement was noted. In cases where children were not able to attend in their supportive seating systems, and where it was possible and safe, children were seated on their parents' laps to provide similar support. The eye-tracking monitor was positioned on a height adjustable table and was supported on an adjustable mount, allowing for changes in position and angle of the monitor relative to the child.

All experiments were controlled using the *Tobii Studio* software suite. When integrated with a *Tobii* eye tracker, the software allows for the controlling and observation of experiments through a graphical user interface (GUI) visible to the researchers. The software records gaze data from the tracker and sessions can be replayed later as a real-time video, A visualisation tool within the software allows researchers to generate and export gaze plots from the data collected, in order to conduct qualitative analysis and provide material for presentations. Raw data can also be exported in a variety of formats for subsequent statistical analysis. The software also synchronises the gaze data with the *Tobii T60*'s user camera, which allows researchers to review a recording of the child in front of the device and to make qualitative observations of behaviour during the sessions.

The software also provides researchers with a "live viewer", providing real-time feedback on the movements of a user's eyes during an experiment. This is particularly helpful when

working with children with CP since it allows researchers to observe that children's gaze is directed towards the screen before continuing with the experiment.

11.4.9 Behavioural Measures Setup

A simple testing setup was developed by the research team to allow the assessment of children's functional vision. The testing materials were designed to be quickly, cheaply and easily replicable by clinicians working with this group of children and to reduce possible distractions in the environment or caused by the presence of the researcher.

With this in mind, the equipment used comprised two black foam-board sheets of A1 size (84.1 x 59.4 cm) positioned in landscape orientation, one above the other to hide the researcher. Both boards were presented vertically, each held in place by "feet" made from the same foam-board. The lower board stood on the floor, with the upper board positioned on two chairs. The upper board had a hole cut in the centre which was shielded by a layer of black mesh, allowing the observer to view the child's eyes whilst remaining obscured and not providing gaze cues or distraction for the child (Figure 47). The boards were arranged at a slight offset, creating a small channel of roughly 15cm in between to allow the stimuli to be presented at eye level without the researcher's hands being visible to the child (see Figure 53 and Figure 55).

The stimuli used were brightly-coloured images of 5cm diameter (shapes of various colours, a sun, a flower and a balloon, see Figure 48) mounted on sticks approximately 40cm in length, cut from the same foam-board material.
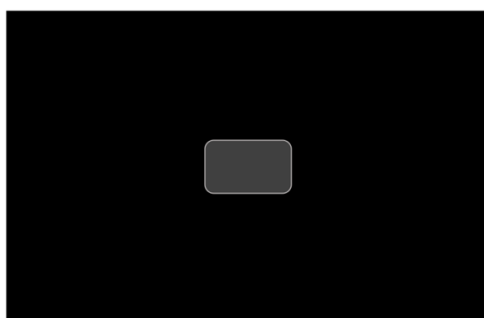
Figure 47 - Graphical representation of the upper board used in the functional gaze control experiment, showing the position of the cut-out hole for viewing children's gaze responses
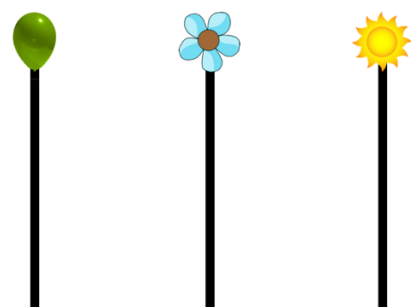
Figure 48 - Graphical representations of stimuli used in functional gaze control assessments

11.4.10 Eye Tracker Calibration

As previously described, reliable calibration of the eye-tracking device is essential to ensure that accurate and valid data is collected. The aims of this activity are therefore to establish whether reliable calibration is possible for this group of children and to document any difficulties observed. All children meeting the criteria (*n* = 39) took part in this phase of the study. Children were positioned in front of the eye-tracking monitor. In all cases, it was endeavoured to position the children at a standard distance of 60cm from the screen, with the eye-tracking camera at a 45° angle relative to the child's horizontal eye-line. This was not always possible to maintain due to the movement difficulties of some children and for some the difficulties in keeping their head still and central during the tests.

The calibration procedure followed in these experiments was based on the procedure set out by Holmqvist et al. (2011). Once positioned in front of the device and given time to get used to the testing environment, children's attention was directed to the screen and the *Tobii Studio* software was checked, using the positioning guide, to ensure that the child's eyes were within the range of the eye tracker.
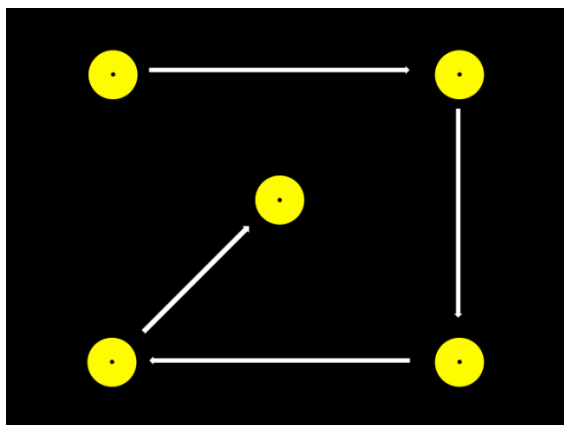
Figure 49 - Graphical representation of the five-point calibration procedure with arrows showing the direction in which the target moves, stopping at each location to allow the eye tracker to sample the position of the users' eyes
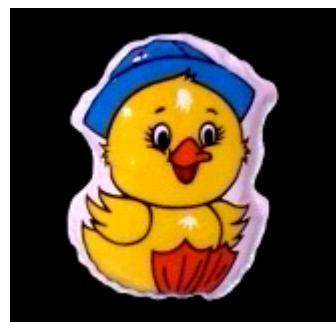
Figure 50 - Example of the "Infant calibration" stimulus from Tobii Studio

Once this had taken place, a calibration procedure was started. The specific calibration process used followed the guidelines set out by the manufacturer of the eye tracker and

software. The usage instructions for *Tobii Studio* (v 3.4.5) recommend that the software's "Regular Calibration" is used as the default. The default settings for regular calibration are set to five calibration points – the colour of the points is red, the background is grey, the speed is set to medium and the calibration is set to use the full screen. Presentation of the dots is sequential and fully automatic (Tobii AB, 2016). For the calibration in this experiment, the colour of the points was changed to yellow, with the background changed to black in order to maximise visual salience (Figure 49).

Before onset of the stimulus, children were given brief verbal instructions to watch the dot (such as "Look, here comes a balloon, can you follow it with your eyes?"). If attention waivered away from the screen during the calibration procedure, the assessor gave a verbal and physical (pointing to the screen) prompt to attempt to refocus their attention (such as "Keep looking, here it comes").

If the system was not able to gather enough data from the five-point calibration after three attempts, then a two-point "Infant Calibration" was attempted. In this calibration, small animations (in AVI format) are displayed in place of the standard dots, accompanied by a sound, which acts as an attention grabber for young children (Figure 50). For the calibration in this experiment, an animation of a toy duck with accompanying bell sound was used. This calibration method is also suggested for those who may have difficulties following instructions given by an assessor during calibration (Tobii AB, 2016).

The infant calibration was controlled by the experimenter. This allowed the experimenter to be sure that the child was looking in the direction of the stimulus before triggering the software to capture the gaze points. It is assumed that the subject will focus on the centre of the calibration animation. When enough data points are collected, the calibration will move on to the next calibration point. The operator can again press the same key to start collecting data. This is repeated for both calibration points (Tobii AB, 2016). Following calibration of the device, all children who were successfully able to calibrate the tracker to the required standard took part in a series of functional gaze control tasks. It is known that the accuracy of an eye tracker is greater when test conditions are as similar as possible to the conditions occurring during calibration (Nyström et al., 2013), so this task took place immediately after the calibration procedure had been completed.

11.4.11 Single Object Fixation

The first experiment involved looking at children's ability to fixate on a single, highly salient object presented against a neutral, black background.

In the eye tracker version of this task, the experiment begins with a blank screen. Children's attention was drawn to the centre of the screen by pointing or tapping a finger in the centre, alongside verbal instruction (e.g. "Let's look for some shapes!"). No fixation cross or similar prompt stimuli was used for this experiment, to avoid any effect caused by the need to disengage from one stimulus and switch to another.
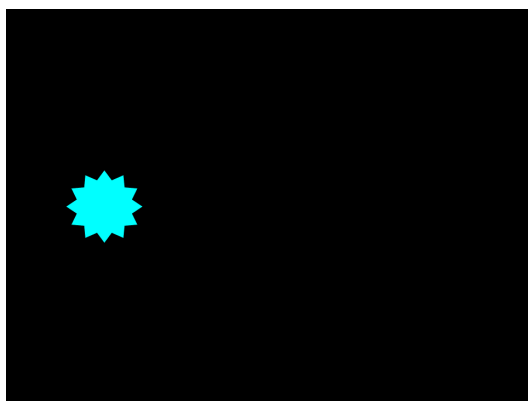
Figure 51 - Sample instance of the single object fixation task, showing the stimulus appearing on the left side of the screen.
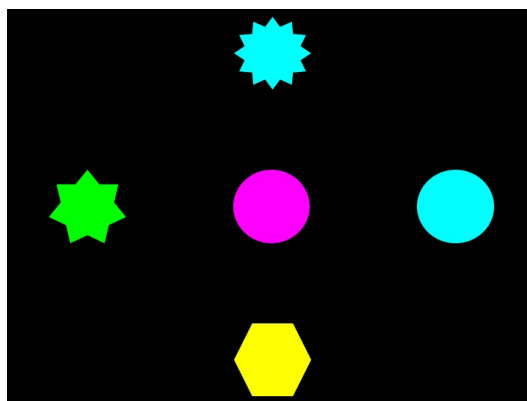
Figure 52 - Composite image showing all five locations, all four shapes and all four colours used in the single object fixation experiment.

Using the *Tobii Studio* live viewer, it was ensured that the child's eyes were directed towards the screen, before the stimulus appeared in one of five locations (top, bottom, left, right or central). A maximum of 32 trials were conducted in groups of 8 presentations of the stimuli, with a short break given between each. The stimuli varied in shape and colour (see Figure 52) to keep children engaged with the activity as best as possible. The location at which it appeared was randomised and counterbalanced and the timing of the appearance of the stimulus was controlled by the researcher in order to ensure that the child was attending to the screen area at the point at which the stimulus appeared. The size of the stimulus remained constant throughout the activity at an absolute measurement of 3.5cm x 3.5cm on the display: giving a visual angle of 3.3° when viewed at a distance of 60cm. A sample screenshot is shown in Figure 51.

A fixation was defined, using the *Tobii Fixation Filter*, as being two consecutive samples (equivalent to 33.2ms at 60Hz sample rate) not separated by a saccade of more than one degree of visual angle (Tobii AB, 2016): indicating that the eyes had remained static on a single point for this duration and allowing a fixation to be differentiated from a saccade passing through the target area. Children scored "1" if fixation was observed within 6 seconds of the onset of the stimulus and scored "0" if no fixation was observed within that time (maximum score = 32).

The behavioural version of the task mirrored this design using the materials described above. Once the child was looking towards the boards a single stimulus was raised, with the image facing away from the child and therefore hidden, into one of five positions (left, right, top, bottom, centre). The stimulus was then rotated so that the image became visible and was displayed for approximately 6 seconds (Figure 53) before being turned back. The stimulus was then moved to the next location and the procedure was repeated. The stimulus was presented twice in each location for a total of ten trials, with the order of presentation ensuring that it did not appear at the same location twice in a row. In order to attempt to get baseline scores for all children included in the study, a parent or familiar adult was asked to gently support children's heads if they were not able to support them in midline themselves for long enough to engage with the trials.
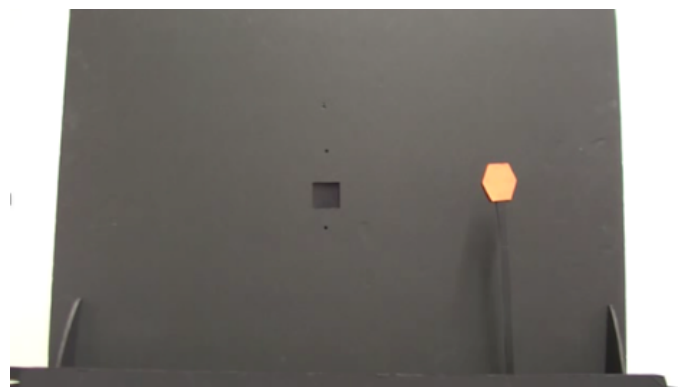
Figure 53 - Screenshot from recording of Fixation task showing stimulus presented in the "right" location

Scorers were asked to indicate whether they felt the child had oriented to the presentation of the stimulus, whether they felt a fixation of two seconds or longer had been achieved, and

how long it had taken for the child to achieve this. Children were therefore given a score of "1" if they fixated on the stimuli within six seconds and a score of "0" if a fixation did not take place within this time (maximum score = 10).

11.4.12 Gaze Switching

Following the single object fixation task, a task to test children's ability to switch their gaze between objects was carried out. This task was based on a modified version of the "gap-overlap" task, which has been widely used (Csibra, Tucker, & Johnson, 1998; Elsabbagh et al., 2009; Karatekin, 2007) in studies of visual orienting in children with autism. This task tests the ability of children to disengage focus from one stimulus and transfer it to another. The current study used only the "overlap" condition, where the initial stimulus remains in place since this is the condition that most directly relates to the functional vision skill of gaze transfer. This also allows looking at the ability of children to inhibit one stimulus in favour of another, as required in the experiments developed over the past three chapters.

Once again, the eye tracker version of this task begins with a blank screen. Once the researcher was sure from checking the *Live Viewer* that the child was looking towards the screen, a central stimulus appeared – either a yellow and orange sun or a pink flower. Both were sized to match the stimuli in the gaze fixation task: an absolute measurement of 3.5cm x 3.5cm on the display giving a visual angle of 3.3° when viewed at a distance of 60cm. However, in this experiment, the stimulus subtended around a central point, giving the visual impression of shrinking and growing or "pulsing" in an out. Once the researcher could see, using the *Live Viewer*, that the child's gaze was focused on the central stimulus, the peripheral stimulus was presented, competing with the central stimulus. The peripheral stimulus appeared either to the left or right and was always a green balloon, sized to match the central stimulus (see Figure 54). The location (left or right) at which the stimulus appeared was randomised and counterbalanced. A maximum of 16 trials were conducted in 2 groups of 8, with a short break between each group.

For each trial, the software recorded whether or not the child had made a fixation within the periphery stimulus area, using the procedure described in the Analysis section below. Children scored "1" for a gaze shift resulting in a fixation in the area of the peripheral stimulus

and scored "0" if no gaze shift was seen within six seconds of the onset of the peripheral stimulus (maximum score = 16).

Figure 54 - Two examples of trials from the gaze shift task, showing the two central stimuli (sun and flower) and the two positions of the peripheral stimuli (left and right)

In the behavioural administration of this task, once the child was looking towards the boards a single stimulus was raised, with the image facing away from the child and therefore hidden, into one of five positions (left, right, top, bottom, centre). The stimulus was then rotated so that the image became visible and was displayed for approximately 6 seconds (Figure 55) before being turned back. The stimulus was then moved to the next location and the procedure was repeated. The stimulus was presented twice in each location for a total of ten trials, with the order of presentation ensuring that it did not appear at the same location twice in a row.
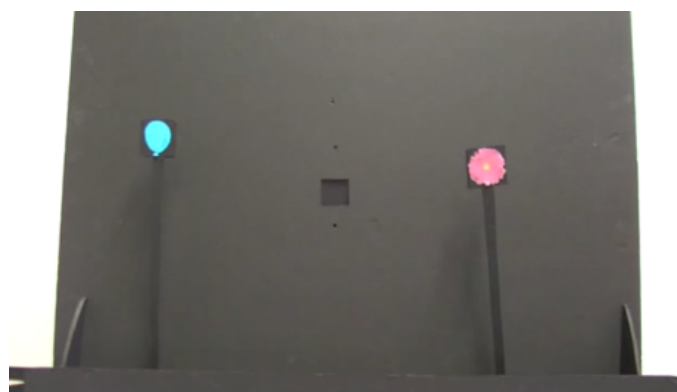
Figure 55 - Screenshot from Gaze Switching task showing both stimuli displayed in competition

In order to help the children to perform to the best of their ability a parent or familiar adult was sometimes asked to gently support children's heads if they were not able to support them in midline themselves for long enough to engage with the trials.

Scorers were asked to indicate whether they felt the child had oriented to the presentation of the stimulus, whether they felt a fixation of two seconds or longer had been achieved. For the purposes of this secondary analysis of the data, and to provide useful comparison with the data obtained via the eye tracker, children were given a score of "1" if they fixated on the stimuli within six seconds and a score of "0" if a fixation did not take place within this time.

11.4.13 Inter-rater Reliability and Recording Setup

As previously, children were assessed on their engagement and performance in the tasks. Engagement in the context of this chapter describes whether a child's eyes were oriented towards the test materials at the time during which the stimuli were presented. Performance describes whether or not children demonstrated the target skill (fixation or gaze switching).

For measures using the eye-tracking technology, the built-in user cam recorded a view of the child's head and shoulders for the duration of the task. All data collected during the sessions was backed up to an external hard drive using *TrueCrypt* file encryption for security. In the behavioural tasks, two digital video cameras with integrated microphones were used, with one focused on the child and the other focused on the boards. At the start of each procedure, the cameras were "synced" using an auditory cue. Video recordings could then be cut together and replayed side-by-side, meaning researchers were able to review the recordings after the experiment to see if the observations made in the test environment would be mirrored by those made retrospectively.

Behavioural measures were scored by two observers, each blinded to the other's scoring. The first observer was positioned behind the boards so that they could see through the hole and observe the child's gaze behaviours from the best possible vantage point – at eye level, directly opposite the child. The second observer stood behind the board setup and slightly to the left or right so as not to distract the child. A score sheet was used to record whether each observer felt the child had exhibited the target functional gaze control skill. The use of two

observers allowed reliability of the results to be checked. A copy of the score sheet is included in Appendix F-4. For a sample of the children, a third observer reviewed the video recordings independently to test whether the behaviours observed by the two "live" observers could be observed in recordings.

GazePlot
Media: p07f14
Time: 00:00:00.000 - 00:00:13.432
Participant filter: All Participants
Number of participants included: 1/1 (100%)
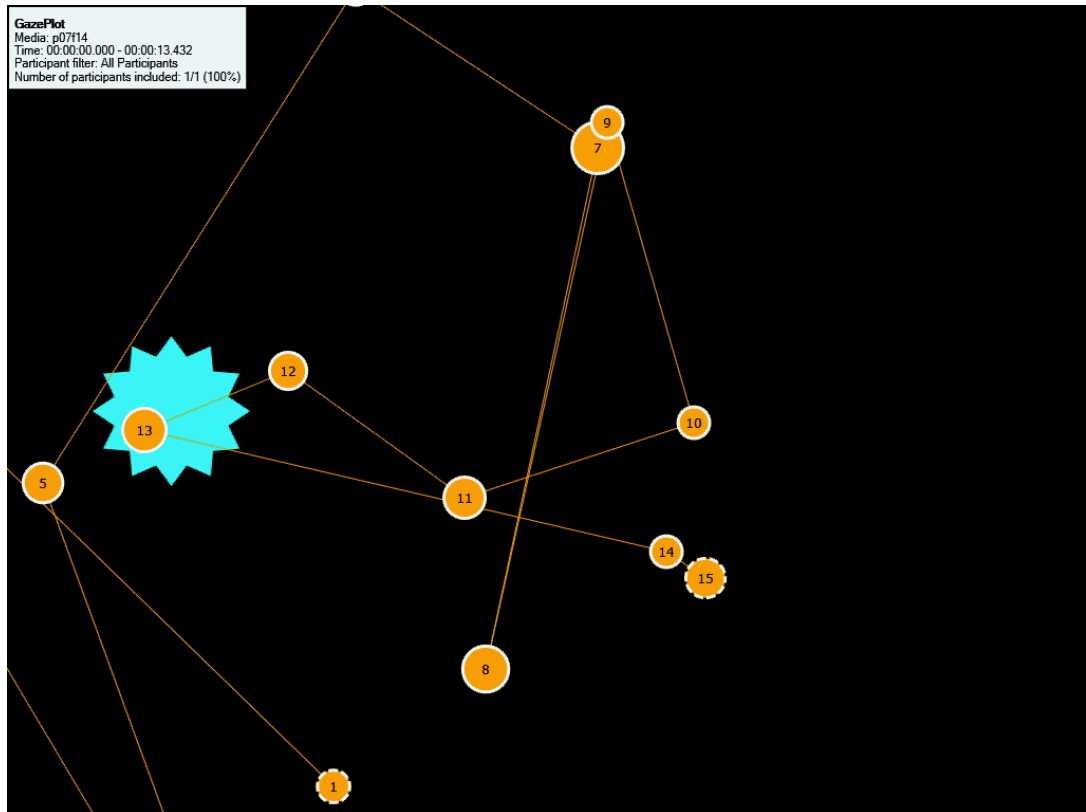
Figure 56 - Sample gaze plot from the Tobii Studio software, showing 15 fixations, one of which fell within the AOI of the stimulus.

11.4.14 Analysis

The *Tobii Studio* software provides feedback on whether each participant in a study has achieved a reliable calibration, which can be conceptualised as a calibration in which the gaze points recorded during calibration do not vary in accuracy and precision to such an extent that the eye tracking software is not able to integrate the results into the tracking algorithm and thus generate reliable gaze point data. Calibration is thus scored "live" and failure to meet the required threshold resulted in the experiment being discontinued. Data on whether children were able to calibrate, and on which calibration protocol was used, was recorded in a spreadsheet and any observations made about the child's behaviour or performance during the task were recorded in field notes kept by the researcher.

For children who were able to calibrate, the *Tobii Studio* software was used to analyse the recorded gaze points (see Figure 56). For each trial, an area of interest (AOI) was retrospectively defined, corresponding to the location and size of the stimulus (Figure 57). The software then analysed whether any instance of fixation had taken place within the AOI in the first six seconds following the onset of the stimulus. Although reaction time to fixation (RTF) was not used to analyse data in this experiment, fixations with an RTF of less than 0.1 seconds were removed from the analysis as, on review of several trials, it was observed that this was likely to indicate that the child's gaze point was already within or very near the AOI at onset of the stimulus.

Analysis of the behavioural measures was conducted by transferring the handwritten forms into *Microsoft Excel* and *SPSS* for analysis. For both the fixation and gaze switching tasks, the data from the two observers was checked for inter-rater reliability. The level or reliability was described as either poor, fair, good or excellent, as advised in the published literature on the development of new assessment tools (Cicchetti, 1994).
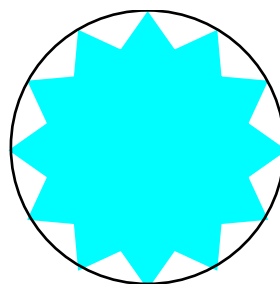
Figure 57 - Sample instance of the AOI
(represented by a black circle) positioned over the
stimulus for analysis.

11.4.15 Note on Data Quality

For all recordings generated, the *Tobii Studio* software provides a percentage score for the Gaze Sample Rate obtained during the recording. This percentage is arrived at by dividing the number of eye-tracking samples with usable gaze data that were correctly identified, by the total number of possible samples (Tobii Technology AB, 2018) and effectively acts as an indicator of the quality of the recording. Thus, a higher score on this metric represents better tracking and a better quality of data. A lower score may reflect participant characteristics

such as a large amount of head movement or physiological differences in the eyes which make them harder to track, technical factors such as poor configuration or setup of the device, or environmental factors such as high levels of ambient light or the presence of distractions in the environment that may cause the subject to look away from the screen (Oakes, 2012).

The average gaze sample rate of children taking part in the current study was 21.6%. Whilst this is lower than many others reported elsewhere in the literature, it was not considered to be prohibitive of carrying out further analysis, since the features of children's gaze being analysed (fixation, switching) do not require the same level of data integrity as other features such as saccadic velocity and microsaccades. It is recognised (Dalrymple et al., 2018) that younger typically developing children can have much lower gaze sample rates than adults or older children because of their tendency to move a lot during recordings and, given the description of the current population of children as being at GMFCS IV or V, it is likely that this accounts at least in part for the low sample rate.

11.5 Results

All children (n = 39) were given the opportunity to take part in the full protocol. The results for each section are summarised in the following sections.

Table 11 - Chronological, language & non-verbal ages of participants (months)

	Mean	SD	Range
Chronological Age	91.11	30.35	40 – 145
Language Age Equivalent	26.24	12.30	11 – 54
Non-Verbal Cognitive Age Equivalent	25.57	13.06	10 – 54

11.5.1 Relationships Between Age Scores

Correlational analysis was performed for all children (n = 39) to examine the strength of the relationships between each of the three age scores: chronological, language understanding age equivalent and non-verbal age equivalent (see Table 11). Examination of means indicated that there was a large mean difference between the chronological and developmental ages of the children included in this study.

Pearson's partial correlation was run to assess the relationship between language age equivalent (M_{lang} = 26.24, SD = 12.30) and non-verbal cognitive age equivalent (M_{cog} = 25.57, SD = 13.06). There was a linear relationship between both groups of scores, as assessed by matrix scatterplots. There was univariate normality for both variables as assessed by Shapiro-Wilk's test (p > .05). There were no univariate outliers as assessed by boxplots. Pearson's correlation established that there was a strong, statistically significant linear relationship between language age equivalent and non-verbal cognitive age equivalent (r(37) = .925, p = <.001). Given the strength of this result, it was once again decided to use only language understanding age equivalent for future analyses.

11.5.2 Calibration

All children (n = 39) attempted a calibration using the procedure described above. Six children (15.4%) were unable to calibrate using either the standard or infant calibration. Observed reasons for non-calibration included an inability to fixate on the target, which may perhaps be indicative of impairment in functional gaze control or a previously unreported ocular-motor difficulty. Other reasons for non-calibration included non-attention to the stimulus, difficulties with head control or maintaining posture and non-compliance with the activity.

A chi-square test for association was conducted between GMFCS level and whether or not children calibrated. This is summarised in Table 11-4. There was no significant association between physical disability and calibration (χ^2(1) = 1.423, p = .233). As two cell frequencies were less than five, a subsequent Fisher's Exact test was conducted, which confirmed that there was no association between these two factors (p = .376).

Table 12 - Calibration by GMFCS Level

	GMFCS Level IV	GMFCS Level V
Calibrated	14	19
Did Not Calibrate	1	5

Whilst it is important to acknowledge the difference in the group sizes and the potential impact of this on the outcome, an independent samples t-Test was run to determine if there were differences in language age equivalent between those children that calibrated (n = 33) and those that did not (n = 6). The language understanding age equivalents of the six children

who did not calibrate were 11, 16, 17, 24, 34, 46 months. There were no outliers in the data, as assessed by inspection of a boxplot. Language age scores were found to be normally distributed on analysis using the Shapiro Wilk's test ($p > .05$), and there was homogeneity of variances, as assessed by Levene's test for equality of variances ($p = .675$). There was no statistically significant difference between the language age equivalents of the children who calibrated (M_{lang} = 26.97 months, SD = 13.04) and those who did not (M_{lang} = 24.66 months, SD = 13.14) ($t(37)$ = .162, p = .872). Children who were not able to calibrate are not included in subsequent analysis as the eye tracking software does not permit data recording without a calibration.

11.5.3 Single Object Fixation: Eye Tracking Results

All thirty-three children who calibrated the eye tracker participated this this activity. As with previous experiments, children were engaged with a varying number of trials (M_{trials} = 13.52, SD = 6.79, $Range$ = 0 − 32) out of the maximum possible 32. Scores for each child were converted to percentages for subsequent analysis. Children achieved a fixation on an average of 37.32% of trials (SD = 32.06, $Range$ = 0 − 100%).
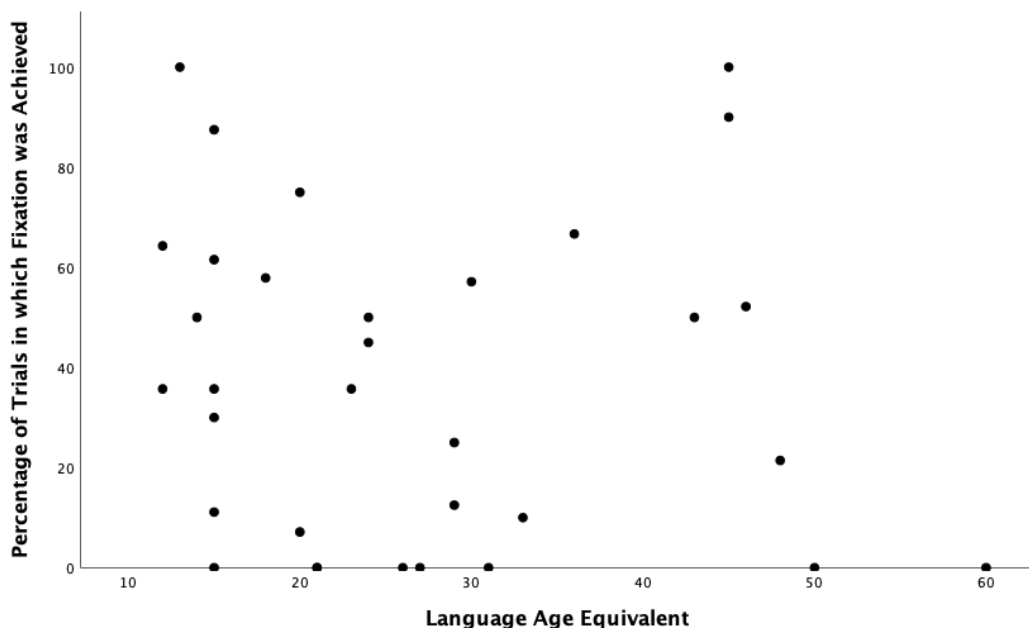
Figure 58 - Graph showing percentage of trials in which each child achieved fixation, plotted against their language understanding age equivalent. Note that data points may overlap.

Correlational analysis was conducted to test the strength of the association between percentage fixation score and the child's language age equivalent. Percentage of trials was shown to be normally distributed on examination with the Shapiro Wilk's test (p > .05). On inspection of a scatter plot (see Figure 58), data was judged to violate the assumption of linearity and hence the Spearman's rank order coefficient was run. All 33 children were included. There was no statistically significant relationship between language age equivalent and percentage of trials on which children achieved a fixation (r_s(31) = -.178, p = .322).
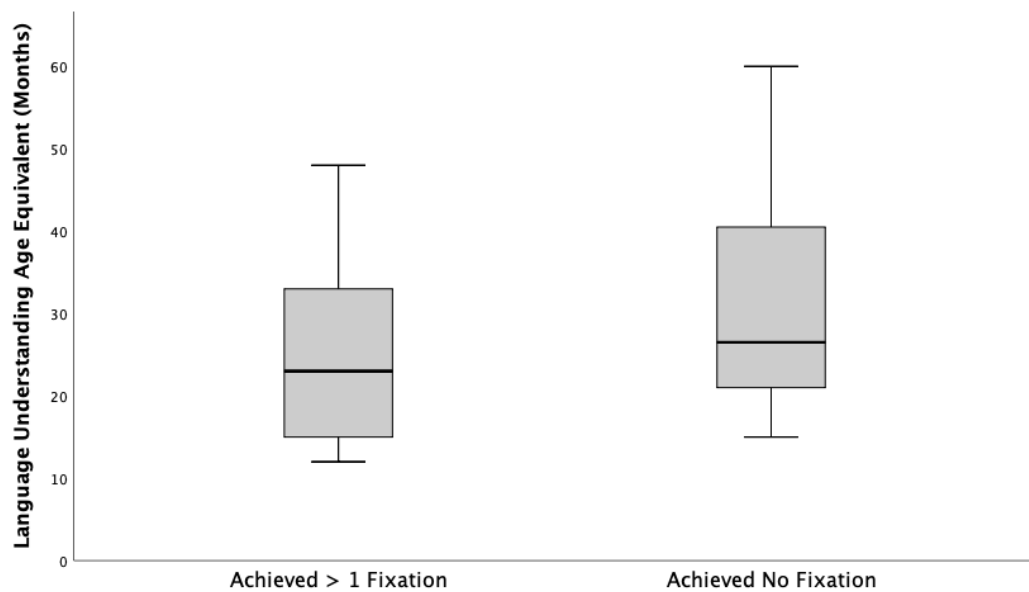
Figure 59 - Box plots showing distribution of language age scores in the groups that achieved and did not achieve any instance of fixation

Of particular interest is the finding that 8 children (24.2%) did not achieve a single fixation within the target AOI. These children engaged with an average of 9.9 trials which, although lower than the average for the group is within one standard deviation from the group mean, indicating that there is nothing remarkable about their level of engagement. An independent-samples *t*-Test was run to determine if there were differences in language age between groups achieving fixation and those who did not. No outliers were identified on inspection of boxplots (Figure 59). There was homogeneity of variances, as assessed by Levene's test for equality of variances (p = .587). There was no statistically significant difference in language understanding age equivalent between the two groups (t(31) = 1.102, p = .279). Therefore children who failed to record any instance of fixation are from across the developmental age range.

Given the relatively high occurrence of strabismus within the group (n = 10, 25.6% of children) and the potential of this to confuse tracking algorithms (K. Holmqvist et al., 2011), an independent t-Test was conducted to determine whether this relationship was significant. No outliers were seen on inspection of boxplots. There was homogeneity of variances, as assessed by Levene's test for equality of variances (p = .061). There was no significant difference between the percentage fixation scores of children with strabismus (M_{fix} = 29.96, SD = 20.38) and those without (M_{fix} = 39.30, SD = 34.59) (t(31) = -.678, p = .503).

11.5.4 Gaze Switching: Eye Tracking Results

All thirty-three children who calibrated the eye tracker participated this this activity. Children engaged in a varying number of trials (M_{trials} = 4.27, SD = 3.43, Range 0 – 11) out of a maximum possible 16. Data was once again converted to percentages for subsequent analysis. Children demonstrated an average percentage gaze switching score of 31% ($Range$ = 0 – 100%). Correlational analysis was carried out to test the strength of the association between percentage of trials in which gaze switching occurred and the child's language age equivalent. Percentage of trials was shown to be normally distributed on examination with the Shapiro Wilk's test (p > .05). On inspection of a scatter plot, data was judged to violate the assumption of linearity and hence the Spearman's rank order coefficient was run. All 33 children were included. There was no statistically significant relationship between language age equivalent and percentage gaze switching score (r_s(31) = .078, p = .667).

11.5.6 Single Object Fixation: Behavioural Results

All children (n = 39) engaged with 10 trials of the fixation task. These trials were scored by at least two observers, as described above. Cohen's Kappa indicated that there was substantial agreement on whether or not the child had orientated their gaze to the stimuli (K = .678).

Children achieved fixation on the stimulus on a mean of 8.38 trials (84%, SD = 2.369, $Range$ = 0 – 10). On examination of a histogram showing the frequency distribution (Figure 60), it was observed that children appeared to fixate on targets more frequently in this task than when using the eye tracker.

Mean = 8.38
Std. Dev. = 2.369
N = 39
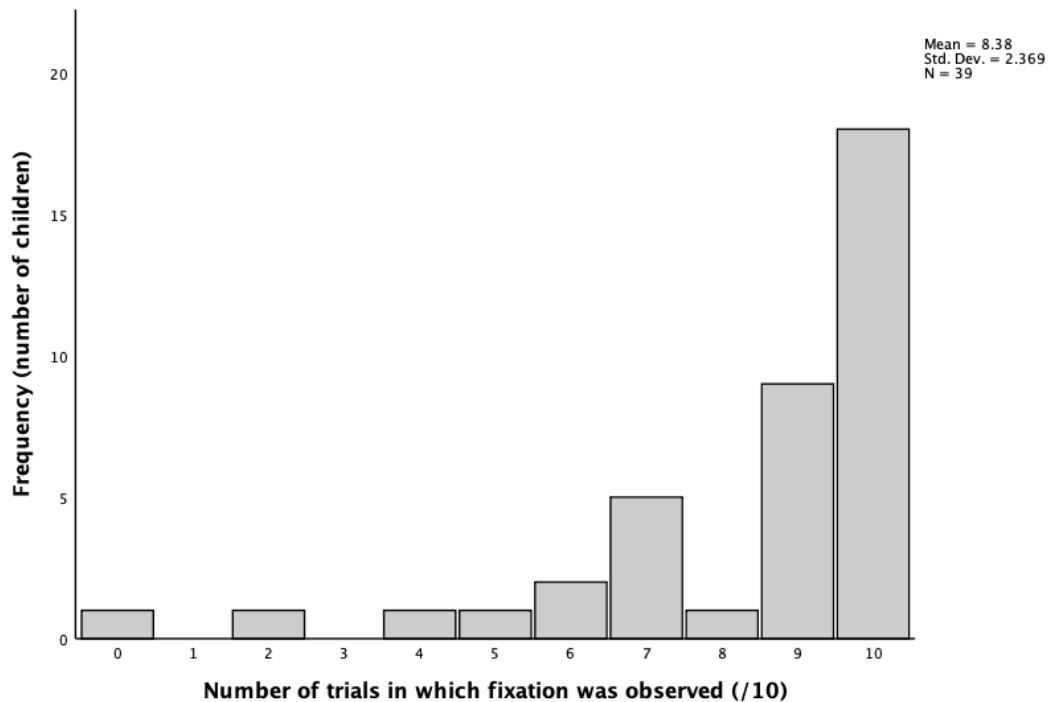
Figure 60 - Histogram showing the frequency distribution of fixations made by children during the behavioural task.

Scores were converted to percentages given the varying level of engagement in the trials and to allow comparison with results obtained through use of eye tracking. Correlational analysis was conducted to test the strength of the association between the percentage fixation score and the child's language age equivalent. Both sets of data were found to violate the assumption of normality on testing with the Shapiro Wilk's test ($p < .005$) so the nonparametric Spearman's rank order coefficient was run. All 39 children were included. Preliminary analysis showed the relationship to be monotonic, as assessed by visual inspection of a scatterplot. There was a significant positive correlation between language age equivalent and percentage fixation score ($r_s(37) = .373$, $p = .019$). Children with higher language score tended to achieve a higher percentage of fixations.

As with the eye tracking experiments, an independent samples *t*-Test was run to determine whether the presence of strabismus influenced the percentage of trials on which a fixation was recorded. Strabismus was noted in 11 of the children taking part in these experiments (28.2%). No outliers were seen on inspection of boxplots for both datasets. There was homogeneity of variances, as assessed by Levene's test for equality of variances ($p = .115$). There was no significant difference between the fixation percentages of children with

strabismus (M_{fix} = 74.55, SD = 30.78) and those without (M_{fix} = 87.50, SD = 19.74) ($t(37)$ = -1.566, p = .126).

11.5.7 Gaze Switching: Behavioural Results

All children (n = 39) took part in this activity. These trials were scored by at least two observers, as described above. Cohen's Kappa indicated that there was moderate agreement between the two observers on whether children had performed a gaze switch (K = .590). Children engaged with a varying number of trials from a maximum of 8 (M_{trials} = 4.59, SD = 2.14, $Range$ = 0 − 8). Performance scores were converted to percentages for subsequent analysis. Children demonstrated gaze switching to the peripheral stimulus on an average of 67.4% of trials (SD = 35.64, $Range$ = 0 − 100).

Correlational analysis was carried out to test the strength of the association between percentage of trials in which gaze switching occurred and the child's language age equivalent. Both sets of data were found to violate the assumption of normality on testing with the Shapiro Wilk's test (p < .005) so the nonparametric Spearman's rank order coefficient was run. All 39 children were included. The relationship between language age equivalent and percentage of trials on which children achieved a fixation was not statistically significant ($r_s(37)$ = .255, p = .117).

11.5.8 Relationships between Functional Vision Skills

Further correlational analysis was undertaken to test the strength of relationships between the two functional vision skills on the behavioural tasks. Spearman's rank order coefficient was run and demonstrated that there was a significant relationship between performance on the fixation task and the gaze switching task ($r_s(37)$ = .339, p = .035).

11.5.9 Comparisons between Eye Tracking and Behavioural Results

In order to effectively compare the results of the behavioural measures with the results from the eye tracking measures, children were divided into two groups based on their performance in the eye tracking tasks: children who either did not calibrate or who subsequently recorded no single instance of fixation (n = 14), and children who calibrated and recorded at least one instance of fixation (n = 25).

Table 13 - Comparison of eye tracker and behavioural performance on fixation task

	No score on behavioural fixation	Score >1 on behavioural fixation	Total
No calibration or no fixation	0	14	14
Calibration and > 1 fixation	3	22	25
Total	3	36	39

When crosstabulation was run (Table 13), it was noted that there was a group of children (n = 14, 36%) who had displayed instances of fixation on the behavioural task, despite not having calibrated or recorded an instance of fixation on the eye tracker. This group of children scored fixation on between 40 and 100% of the behavioural trials (M_{fix} = 84.3%, SD = 19.1%). Of particular note was that six of these children achieved fixation on 100% of behavioural trials, two of whom were not able to calibrate and the remaining four of whom did not register any fixations using the eye tracker.

Table 14 - Comparison of eye tracker and behavioural performance on overlap task

	No score on behavioural overlap	Score >1 on behavioural overlap	Total
No calibration or no overlap score	5	15	20
Calibration and overlap score > 1	0	19	19
Total	5	34	39

Similarly, 15 children who either did not calibrate or did not show instances of gaze switching on the eye tracking task showed at least one instance of gaze switching on the behavioural task (Table 14).

11.6 Discussion

This chapter addressed the following questions:

1. Are children with cerebral palsy able to calibrate an eye-tracking computer with enough precision to allow the gathering of reliable data on their eye movements?

2. Is an eye tracking computer a useful tool for collecting information on the functional gaze control skills of this group of children?

3. How do the same group of children perform on behavioural functional gaze control tasks?

4. What is the profile of functional gaze control skills in this group of children?

This study has highlighted mixed findings in use of an eye tracker with this population of children. In particular, the fact that the calibration procedure acts as an effective "entry barrier" to taking part in the experiments means that some children whose functional gaze skills might have benefited from investigation are excluded by the need for accuracy imposed by the technology.

The calibration rate reported in this study (84.6% of included children calibrated the device) is lower than rates reported elsewhere in the literature (Light & McNaughton, 2014b; Wilkinson & Light, 2014). The rates reported here, whilst not for matched groups of children, are lower than the calibration rates reported for typically developing children (92 – 100%) and children with downs syndrome (88%). However, they are similar to those reported for children with intellectual or developmental disabilities (83%), despite the children in this study having severe movement disorders.

If one considers, as proposed by Nyström and colleagues, that the calibration procedure used in these experiments constitutes a single object fixation exercise (Nyström et al., 2013), it is interesting to observe that the single object fixation task included in this chapter had such variable results, despite all children completing the calibration exercise. In addition to the

group who did not calibrate (n = 6), a further group (n = 8) of children did not record any instance of fixation, despite calibrating. These children were from across the developmental age range tested. When the scores of these groups were compared against the equivalent scores on the behavioural measures, all children were found to have scored on the behavioural task for gaze fixation. Further, the group was seen to have achieved fixation on an average of 84.3% of trials in which they engaged with the behavioural task. This would indicate that these children failed to score on the eye tracker tasks for reasons related to the technology setup and the ability of the device to accurately track children's eyes, rather than because they lacked functional vision skills. Children's heads were supported during the calibration procedure if they had difficulties holding their heads up without help. Once these supports were removed, it is possible that their poor head control contributed to their reduced ability to score on the fixation tasks. Therefore the answer to the first research question is that some children are able to calibrate an eye tracker with sufficient precision for it to be useful in the collection of data, but there are some children who are not, meaning there is potential for their abilities to be "missed" through testing in this way.

The requirements for accuracy may also make eye tracking an impractical way to test the functional vision skills of children with severe bilateral CP. The data sample rate was very low, and this further contributed to uncertainty about whether the percentage of recorded fixations (an average of 37% for single object fixation and 32% for gaze switching) was reflective of children's actual performance or of the device's ability to track them accurately. This is compounded by the difference between these percentages and their equivalents on the behavioural tasks (84.5% for single object fixation and 67% for gaze switching). Taken together, the results from calibration and these findings about accuracy answer the second research question; indicating that the eye tracker is not a useful tool since the rates of attrition and the risk of underestimating children's performance is too great.

As an addendum to the above points, the results of these experiments support the use of eye-gaze (as opposed to eye tracking) technology in the experiments described in the final chapters of this thesis. The much lower calibration requirements and the ability to support children by reducing the accuracy required for selection is vindicated by these results, where accuracy may have been a contributing factor to the poor performance of some children.

In contrast to the eye tracking tasks, the behavioural measures of functional gaze control seem to offer greater inclusivity, with all children able to at least take part in these measures. Many children were able to show evidence of skills that they had not been able to show on the eye tracker or to show better performance using the behavioural task. Given the high rates of agreement between the two observers on the behavioural tasks, it seems likely that the eye tracking paradigm may underestimate some children, even when they are able to calibrate. For children who may have difficulty maintaining head position, behavioural observation also presents clear advantages. The possibility of presenting the stimuli at different locations can be explored, offering children the best chance to demonstrate their functional gaze control abilities. In addressing the third research question, the results of the behavioural measures indicate a generally higher level of performance for these children when tested using behavioural measures than was shown by the eye tracker.

Setting aside the question of technology momentarily, what emerges from both the eye tracking and behavioural results is a picture of a population of children whose functional vision skills are highly variable. This answers the fourth research question addressed in this chapter and supports the idea that functional vision skills are important to consider, given their relevance to eye-gaze control. Returning to the principles of the Matching Person and Technology model and assessment process, the variability observed here supports the idea that these skills should be measured in individuals being considered for eye-gaze technology, since their presence, absence or any reduction in performance may well play a role in determining children's likely performance.

Whilst the outcome of the behavioural measures of fixation seemed to suggest a positive correlation between developmental age and performance on the tasks, it should be noted that all children included in the study had a language understanding age equivalent of above 40 months (3 years 4 months). Given that clinical experience suggests the population of children who are considered for eye-gaze technology are frequently younger than this, there is potential for younger children to have a different and reduced profile of ability. The fact that considerable variability was still evident in this older population suggests that these skills cannot be assumed to be present in any particular group of children and adds more weight to the idea that these skills are important to measure and understand when working with this clinical population.

11.7 Conclusion and Implications for Future Work

From a pragmatic perspective, the use of eye tracking technology is not indicated as a way to test functional gaze control skills, since it is too costly, both in terms of time and the rate of attrition. This technology may have applicability to test other skills in this population, but the results presented here demonstrate that it is simply not a practical choice for gathering the information needed. As discussed above, behavioural measures of functional gaze control offer a more inclusive, more flexible and more reliable way to gather this information in the target population of children with CP. Quite simply, the behavioural approach is more inclusive and provides better insight into the skills of this group. A behavioural approach will therefore be taken to assessing the functional vision skills of these children in the final experimental chapter of this thesis, which looks at the impact of these skills on performance with eye-gaze technology.

Chapter 12

Eye-Gaze Performance in Children with Cerebral Palsy

12.1 Introduction

Experiments described previously in this thesis have indicated that typically developing children of above 24 months can make some use of eye-gaze technology to engage with simple cause and effect tasks. Children below 24 months struggled with the eye-control tasks. It has also been demonstrated that for children with cerebral palsy (CP) functional vision skills, in particular the ability to fix and transfer gaze, can be highly variable.

Returning to one of the underlying theories on which this work is built, it is reasonable to assume that functional vision abilities may play a role in determining how successful children are when using this technology, since many of the skills overlap with those required to purposefully control an eye-gaze device. Recognising the need to understand the strengths and needs of the individual set out in the Matching Person and Technology (MPT) model (Scherer, 2004) and others like it, it is important to understand the impact of these functional vision skills on eye-gaze performance.

This final experimental chapter brings together the behavioural measures of functional gaze control and the eye-gaze games developed in previous chapters. The intent is to replicate the eye-gaze intervention tasks described in Chapter 9 with a small group of children with severe bilateral CP. Given the potential influence of functional gaze control skills in this group on accessing eye-control technology, this chapter examines the relationship between functional gaze control and performance on eye-control activities.

12.2 Experimental Design

This section of the study used a small-scale cross-sectional design to address the research questions below. As children with CP have a greater instance of deficits in language understanding (M. Clarke et al., 2016; Geytenbeek et al., 2010; Sigurdardottir & Vik, 2011), testing of participants' language comprehension was once again carried out in addition to the target measures. To ensure that the children recruited had an established understanding

of cause and effect, a brief play-based task was included. This task also served to introduce children to the testing environment and to the experimenters in a fun and relaxed way.

The experiments in this section of the thesis therefore take children's language age equivalent, functional vision classification score and the testing phase (baseline, intervention, post-intervention) as independent variables and engagement with the task and the number of effective stimuli selections as the dependent variable.

12.3 Research Questions

The specific research questions addressed by this final chapter are:

1. What is the relationship between functional vision skills and performance with eye-gaze technology in children with CP?

2. What is the relationship between developmental age and performance with eye-gaze technology in children with CP?

3. What impact does explicit teaching and prompting have on the performance of this group, and can any improvement in performance be retained?

12.4 Methods

The following sections describe the methodology of this first group of experiments, as well as the participants and recruitment strategy.

12.4.1 Recruitment

Children were recruited to the study from two special education primary schools in Kent and London. Initial approaches were made to the manager of each centre by the researcher, which consisted of a copy of the protocol, a covering email detailing the background to the work and a request for their participation. If agreed, teaching or therapy staff were contacted and asked to identify children who met the key inclusion criteria of:

- having a diagnosis of CP (GMFCS IV or V)
- being aged between 4 and 10 years

Children were not proactively recruited based on their language understanding or developmental levels, as the intent was to look at the pattern of skills in this group. Recruitment aimed to identify children with a range of language and developmental abilities, including those below the 24-month level identified in the previous experiments, in order to look at patterns of performance in a group. The group of children recruited therefore represent an opportunity sample, which is consistent with the study design used. Previous experience of using eye-gaze technology was not used to include or exclude children from the study. It was considered important to document this, however, since the use of eye-gaze technology was a novel activity for all the typically developing children previously tested and this may not be the case for children with CP. The only exclusion criteria that were put in place were those that would impact on children's participation in the task. Therefore, staff identifying children for the study were asked not to put forward children with one or more of the following:

- Profound / severe sensorineural hearing loss
- Significant visual acuity loss not due to correctable refractive errors
- Untreated epilepsy
- Confirmed oculomotor dyspraxia

Children were identified by staff at each centre and initial approaches were made to the parents of children meeting the criteria by these staff. If parents were interested, information sheets and opt-in consent forms were provided for them to read and sign, along with the details of the researchers if they had any questions. Copies of the information sheet and consent forms are included in Appendix E-2 and E-3. Parents were told that they may withdraw their children from the study at any point and given assurances that experiments would be suspended if children appeared fatigued or distressed.

12.4.2 Ethical Approval

Ethical approval for this section of the study was granted by University College London Research Ethics Committee, as an amendment to the ethical agreement used in previous chapters (Project ID 1328/009). The extension detailed the new population of children with CP, as well as changes to the experiment design, the addition of the teaching phase and post-

intervention testing phase. A copy of the amendment request and approval email is included in Appendix E-1.

12.4.3 Participants

Nine children (7 male, 2 female) were recruited to the study, aged between 55 and 119 months. Children were recruited as an opportunity sample and were not proactively recruited on the basis of diagnosis, but rather to reflect the range of children often considered to be candidates for introduction to eye-gaze technology. Participant characteristics are summarised in Table 15 below.

Table 15 – Participant Characteristics

Participant ID	Gender	GMFCS Level	MACS Level	CFCS Level	Previous Eye-Gaze User?	Wears Glasses?
P01	M	V	IV	II	No	Yes
P02	F	V	IV	II	No	Yes
P03	M	V	V	V	Yes	No
P04	M	V	V	II	No	Yes
P05	F	V	V	V	Yes	No
P06	M	V	IV	V	Yes	No
P07	M	V	V	V	Yes	Yes
P08	M	V	IV	II	No	Yes
P09	M	V	IV	III	No	No

12.4.4 Equipment and Testing Environment

Children were tested in a familiar room in each of the centres which was separate from classrooms and teaching spaces. To minimise distractions, children were given time at the start of the sessions to get used to their surroundings and to the people in the room. As with previous experiments, children were accompanied by a familiar adult at all times so that they would feel relaxed. Assent was gained from each child at the start of the testing session by asking them if they were happy to play some games with the experimenter. This was reaffirmed at various points during the session and children were permitted to opt out or to take a break at any point. Where fatigue was noted, the testing was split over two sessions.

The eye-gaze control device used was the *Mobi 2* from *Jabbla*, which had a *Tobii PCEye Go* eye-gaze camera. The system was loaned to the project by the manufacturer's UK supplier,

Techcess Ltd. A full description of this device is included in Chapter 9 of this thesis. The device was setup according the manufacturer's specifications and positioned out of direct sunlight to maximise performance. The device was mounted on a *REHAdapt Tele-Lock* rolling floor mount, which offers precise adjustment of height and angle; allowing the device to be adjusted appropriately for children of different heights and in different wheelchairs or seating systems. As previously, the device was positioned individually for each child so that they were seated at the distance from the screen specified in the manufacturer's usage instructions.

The experiments were once again presented in the *Mind Express 4* (ME4) software, with the same design, operation and layout as reported in Chapter 9.

12.4.5 Procedure

Prior to meeting with each child, a conversation with a member of school staff identified whether children had any previous experience with eye-gaze technology and whether there was anything specific that might impact on the running of the experiment (fatigue, nervousness around new people etc.). During this preliminary conversation, school staff were asked if the child typically wore glasses and, if so, it was ensured that these were available for the duration of the session. Children, who were accompanied by a familiar adult, were then met at the door of the room by the researcher who introduced themselves and checked that they were happy to participate. The way in which each child signalled *yes* and *no* was identified for use during the testing session. On entering the room, children were introduced to any other people present and told what was going to happen. They were told that they could stop or take a break at any time. Adults accompanying children into the testing room were asked not to provide children with specific help or pointers during the eye-gaze tasks. They were also asked to notify the research team if they felt that the child was showing signs of fatigue.

12.4.6 Cause and Effect Measure

In line with the previous experiment, a simple cause and effect measure was implemented as part of the protocol. Children were introduced to this task on entry to the room, meaning that it served the dual purpose of establishing the presence of this skill and also being an "ice breaker" to introduce them to the environment and the research team. The measure chosen

was a play-based task (Sharma et al., 2014) using a switch-adapted toy – a rabbit which hopped and jumped when the switch was pressed. The rabbit was placed on a table or on the child's wheelchair tray, and the researcher presented the button (a green *Jelly Bean* switch with 65mm activation area) next to the toy, before modelling what happened when the switch was pressed. Where children were not able to use their hands to activate the switch, school staff were asked what the child's most reliable movement was, or if they had previously used a switch with any other body part, and this was used instead. Children were then given the opportunity to explore the switch themselves and their responses were observed. If children pressed the switch to activate the toy or made purposeful attempts to do so, and responded when the toy moved, they were scored as having established cause and effect with physical objects.

12.4.7 Assessment of Functional Vision

In the time between the experiments detailed in Chapter 11 and this final round of data collection, the work begun by the *Functional Gaze Control Skills in Young Children with Cerebral Palsy* project was expanded upon by another team based at UCL. This work resulted in the development of a subsequent measure: The *Rapid Assessment of Functional Near Vision* (*FunVis*). It was decided that the *FunVis* assessment would be used as part of the final protocol, since it had been demonstrated to be an effective and reliable tool for observing and documenting the functional vision skills of children with CP (M. Clarke et al., 2020, submitted for publication).

The *Rapid Assessment of Functional Vision* (*FunVis*) procedure allows behavioural observation of a child's functional vision, in particular their ability to fixate on a single item, track a moving item and switch their gaze between two items. The *FunVis* provides an initial, five-point screening for functional vision, using different coloured targets – two smiling faces, as shown in Figure 61. The targets were 5cm in diameter and were mounted on sticks of roughly 20cm in length for easy manipulation and display. Each of the five functional gaze control probes is scored as either "achieved" or "not achieved". If a child scores more than two items as "not achieved" then it is suggested they may have difficulties which will impact on their functional use of vision. In such situations, the assessment recommends consultation with a vision specialist. It was decided to use this pass / fail criterion to classify children into

two groups for subsequent analysis: those for whom the test demonstrated functional vision difficulties (a score of 1, 2 or 3), and those for whom it did not (a score of 4 or 5).
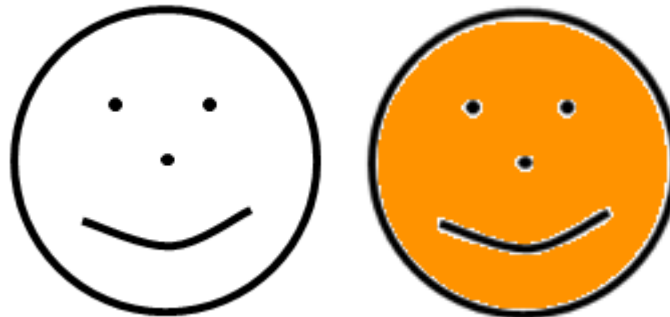
Figure 61 - The white and orange smiling face targets used in the FunVis assessment.

12.4.8 Assessment of Receptive Language

Children's language understanding was then tested using the Auditory Comprehension subscale of the *Pre-School Language Scale – 4th Edition* (PLS-4UK; Zimmerman, Pond, & Steiner, 2009). The use of this test is discussed in more detail in Chapter 6. This was adapted for each child according to their individual needs; either through the use of partner-assisted scanning or fist-pointing if the child had sufficient upper-limb control. Children were scored by the assessor and by another observer, to ensure that any responses were interpreted reliably. Where children were known to staff at school, or had recently had a different language assessment, advice was sought on the point at which to start the assessment in order to minimise fatigue. If children had been tested using the PLS-4UK in the past twelve months, this result was requested. This was not the case for any of the children recruited to the study, however.

12.4.9 Eye-Gaze Calibration

As with previous studies, a five-point calibration was attempted. If this was not possible, a two-point calibration was tried. As discussed in previous chapters, the "snapping" feature of the ME4 software, together with the size of the targets, allows for calibrations on smaller number of points to be used with enough accuracy to complete the game. Children's favourite colour was used for the calibration stimulus, which was set against a highly contrasting background.

12.4.10 Eye-Gaze Target Measures

Following calibration, each child attempted the same series of eye-gaze tasks as described in Chapter 9 and shown in schematic form in Figure 62. Children were first shown a learning phase, where the active stimulus (an adult female in a blue t-shirt) appeared six times. Selecting this using by dwelling on it for a period of 1.0 seconds played one of six randomly selected five second video clips of the female adult completing a novel task, such as playing with a toy or blowing bubbles, each with accompanying sound. The video played in the same area of the screen and at the same size as the stimulus that triggered it. Selecting the inactive stimulus (an adult male in a yellow t-shirt) had no effect and it remained on screen for six seconds, before disappearing and reappearing at another location after a gap of two seconds.
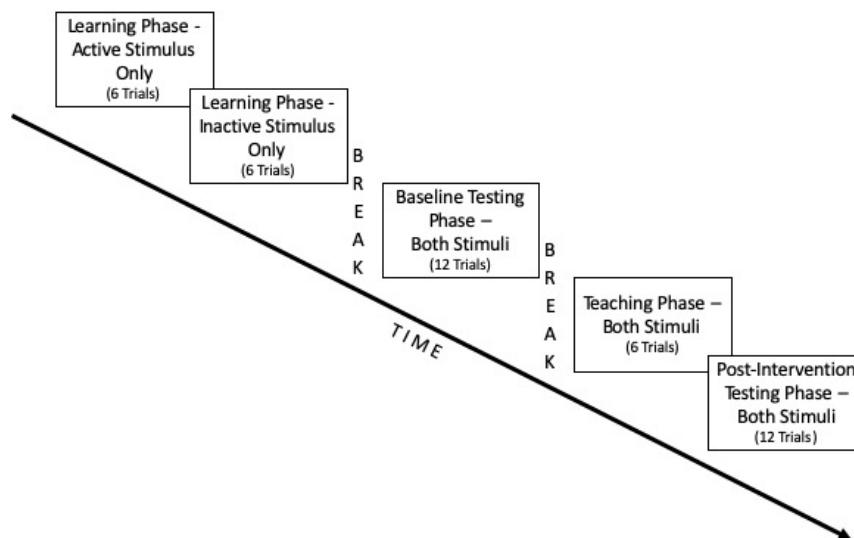
Figure 62 - Schematic diagram of the experimental procedure. This procedure was replicated twice for touchscreen and eye-control modalities.

Following a break, children then attempted the baseline testing phase, in which both stimuli appeared on screen together in separate locations. The stimuli pairing was presented twelve times with the stimuli in different, randomised locations. The child was given no specific instruction during this phase of the trial, with only general prompts to engage with the task and non-specific praise given. When the child selected the active stimulus, they would again be shown one of the videos as described previously. The researcher would then mark the score sheet with a "1". If they selected the inactive icon, the screen would go blank for two seconds, before displaying the buttons again in two different locations. This was considered to end that particular trial and was marked with a "0" on the score sheet. If the child

repeatedly selected blank areas of the screen or if they became distracted and were not focusing on the screen for approximately ten seconds, the researcher would advance the software and the stimuli would again be presented in two new locations. This was also considered to end the trial and was marked with an "X" on the score sheet, with the reasons being recorded. After twelve trials, the software displayed the "well done" message.

This was followed by the teaching phase, in which a further six trials with both stimuli were accompanied by causal language instruction (see Chapter 9), feedback and coaching for the child. During this phase, children were told:

- That the goal was to look at the effective stimulus until it played a video ("You need to look at the lady to make the video play")
- That the ineffective stimulus would not do anything when looked at ("Nothing happens when you look at the man")
- That the cursor on the screen was being controlled by their eyes ("The red box shows where you are looking")
- That the dwell progress marker must complete in order for the video to play ("You need to look until the circle goes all the way round")

Feedback given was more targeted and explicitly referenced the activity and the actions of the child, such as "Well done! You played the video by looking at the lady!". Errors were also responded to with corrective feedback, such as "Oh dear! Looking at the man doesn't play the video! Try looking at the lady instead!". This was accompanied by pointing to the relevant items on the screen.

Following a short break, children were then shown the post-intervention phase of the trial, which replicated the baseline phase: a further 12 trials of the active and inactive buttons appearing together on screen. As with the baseline trials, no task-specific feedback was given, although general encouragement and praise was given to help children stay on task.

At the end of the experiments, children were given a sticker as a reward for participating and were thanked for taking part.

12.4.11 Scoring

A score sheet was used to record details of the children and their performance on each phase of the eye-gaze trials described above. A copy of the score sheet is included in Appendix D-4. This sheet was completed by the person working with the child and by another observer. In addition to recording whether a correct selection had been made, the score sheet also allowed the researcher to record field notes and observations for use in analysis.

12.5 Results

All children involved in the study (*n* = 9) took part in the background measures of vision, cause and effect and receptive language. Results of the language assessment are presented in Table 16 below. Since the results of the language assessment indicated that these children all had learning difficulties, children's language understanding age equivalent was used for analysis of the results rather than chronological age.

Table 16 - Chronological Age, Language Understanding Age Equivalents

Participant ID	Chronological Age (Months)	PLS-4 Language Understanding Age (Months)*
P01	55	36 – 41 (38.5)
P02	107	36 – 41 (38.5)
P03	119	12 – 17 (14.5)
P04	114	24 – 29 (26.5)
P05	118	18 – 23 (20.5)
P06	116	12 – 17 (14.5)
P07	79	12 – 17 (14.5)
P08	84	66 – 71 (68.5)
P09	114	24 – 29 (26.5)

* Language ages are scored in bands, with median scores in brackets

12.5.1 Functional Vision Results

The *FunVis* protocol was carried out with all children. Children's functional vision was scored using the method described above. The results are summarised in Table 17 below. As discussed, children were given a score out of 5 and this was used to nominally allocate them to a group for analysis: scores of between 1 and 3 were allocated to the poor functional gaze control group (*n* = 4) and scores of 4 or 5 were allocated to the good functional gaze control group (*n* = 5).

Table 17 - Functional Gaze Control Scores and Subsequent Group Allocation

Participant ID	*FunVis* Score	Functional Gaze Control Group
P01	4	Good
P02	5	Good
P03	4	Good
P04	2	Poor
P05	4	Good
P06	1	Poor
P07	0	Poor
P08	5	Good
P09	3	Poor

As the group sizes were small, statistical analysis should be treated with caution. A scatter plot was generated to better illustrate the relationship between language understanding age equivalent and scores on the *FunVis* assessment. This is shown in Figure 63 below.
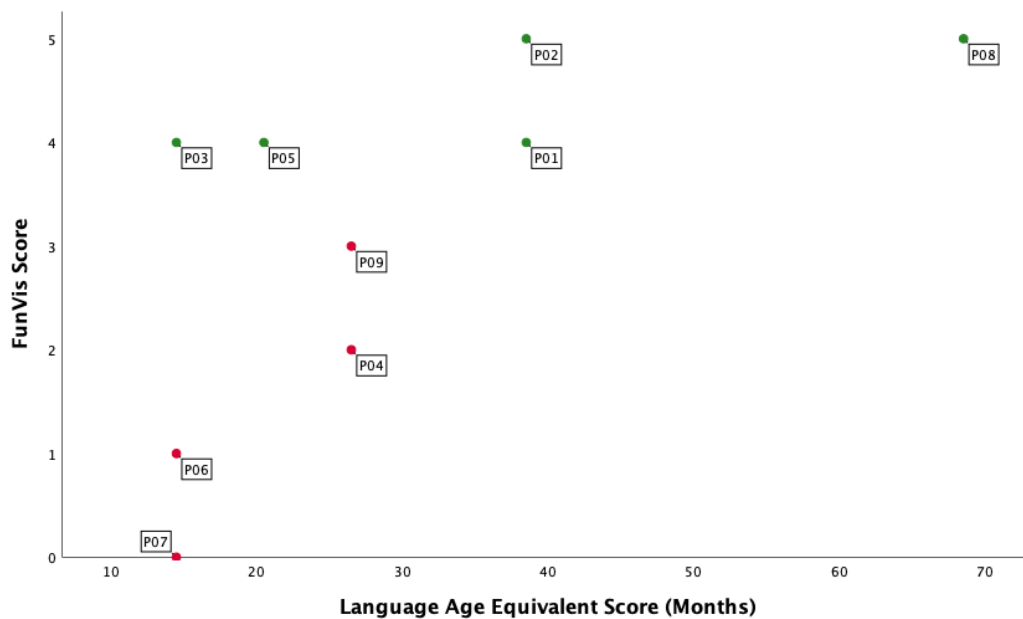
Figure 63 - Children's functional vision skills (as measured using the FunVis assessment) plotted against language understanding age equivalent.
Data points are colour coded to indicate whether children were subsequently classified as having good (green) or poor (red) functional gaze control skills.

Analysis of this scatter plot indicated that there is no obvious relationship between children's language understanding and their performance on the functional vision tasks. Statistical analysis was conducted to confirm this, however as the groups are both small, this analysis

is purely indicative and was conducted to confirm the observations from the scatter plot. Due to the small numbers involved, the Mann Whitney U test was used for this analysis. Language understanding age equivalent scores for the good functional gaze group (mean rank = 6.00) and the poor functional gaze group (mean rank = 3.75) were not statistically different (U = 15, z = 1.257, p = .286).

13.5.2 Cause and Effect with Physical Objects

All children taking part in the study were able to use the toy in the initial play-based assessment as described above and therefore demonstrate understanding of cause and effect with real objects. Seven children activated the switch using their hands and two activated it using their head, with the switch positioned at one side or the other.

12.5.4 Calibration

Several children attempted a five-point calibration but had difficulties maintaining their head control for long enough to complete this. In these cases, a two-point calibration was subsequently run. Eight children (88.88%) were able to calibrate the device using a two-point calibration, with one (P07, from the poor functional gaze control group) not being able to achieve calibration. It is worth noting that the child who was not able to calibrate also had the lowest language understanding age equivalent score in the group with a median score of 14.5 months.

As discussed above, the size of items and the assistance provided by the software meant that a lack of calibration was not considered to be a barrier to continuing with the activities. It was however notable that the child who was not able to calibrate also failed to score on either of the learning phases in the experiment, with field notes indicating that they were not able to orient their eyes reliably to the screen.

12.5.5 Performance on Learning Phases

All children (n = 9) attempted the learning phases as described above. In previous experiments with typically developing children, completing all six trials of the effective learning phase has been a requirement. However, with the group of children with CP, this was not practical, as several children were not able to register a fixation on all six, although the opportunity to engage with six trials was given to all children. Children completed an

average of 4.88 trials (*SD* = 1.356, *Range* = 3 – 6). The same child (P07) who was not able to calibrate also did not complete any trials on the effective button learning phase.

Two children (P04, P09) were not subsequently able to complete any trials of the ineffective button despite having the opportunity to engage with all six trials. It is of particular relevance to this thesis that both these children were from the group described as having poor functional gaze control skills. Children scoring on the ineffective learning phase (*n* = 6) demonstrated fixation on the stimulus on an average of 3.5 trials (*SD* = 1.643, *Range* = 2 – 6).

To further investigate the relationship between functional vision skills and performance on the learning phases, children's scores from the effective and ineffective learning phases were added together to give a total possible score of 12. These scores were then plotted on a graph to show the spread of performance within the good and poor functional gaze control groups (Figure 64).
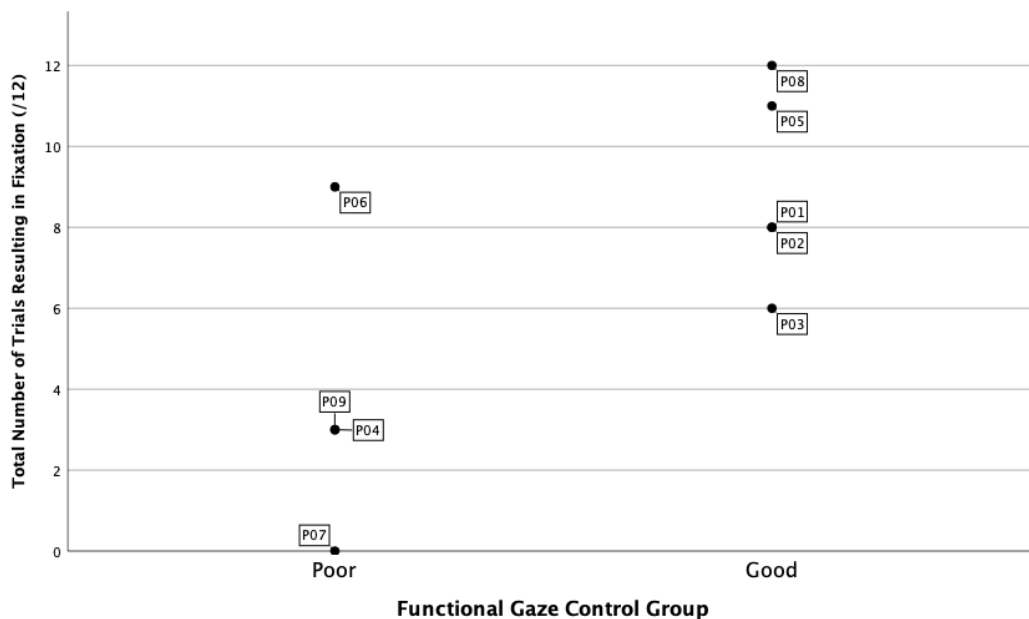
Figure 64 – Plot showing the comparative performance on the learning phases of children with good and poor functional gaze control skills.

12.5.6 Withdrawals from Protocol

One child (P08, from the good functional gaze control group) attempted the eye-gaze activity and was able to calibrate and complete both the effective and ineffective learning phases, scoring six out of six on both. However, technical issues then occurred with the device while

implementing the baseline testing condition and the child opted out due to frustration, refusing to continue even after the problems with the tracker had been rectified. This child was therefore excluded from further analysis. Children who had not fully completed the learning phase (*n* =3, P04, P07, P09) were also removed from subsequent analysis, leaving a group of five children attempting the baseline phase (Table 18).

Table 18 - Children's performance on eye-gaze tasks

Participant Number	PLS-4 Language Understanding Age (Months)*	Functional Gaze Group**	Previous Eye-Gaze User?	Calibration	Learning Phase Total Score (/12)	Baseline Phase Percentage†	Post-Intervention Phase Percentage‡
P01	36 – 41 (38.5)	Good (4)	✗	✓	8	25%	75% (+50)
P02	36 – 41 (38.5)	Good (5)	✗	✓	8	100%	67% (-33)
P03	12 – 17 (14.5)	Good (4)	✓	✓	6	75%	83% (+8)
P04	24 – 29 (26.5)	Poor (2)	✗	✓	3	-	-
P05	18 – 23 (20.5)	Good (4)	✓	✓	11	58%	42% (-16)
P06	12 – 17 (14.5)	Poor (1)	✓	✓	9	17%	-
P07	12 – 17 (14.5)	Poor (0)	✓	✗	0	-	-
P08	66 – 71 (68.5)	Good (5)	✗	✓	12	-	-
P09	24 – 29 (26.5)	Poor (3)	✗	✓	3	-	-

* Language ages are scored in bands, with median scores in brackets

** FunVis scores in brackets

† All percentages rounded to nearest whole number

‡ Change from baseline percentage scores in brackets

12.5.7 Performance on Baseline Phase

As stated above, the baseline task is made up of 12 presentations of a hybrid condition featuring both the effective and ineffective stimuli. Four children engaged with all 12 trials; one child (P02) could only engage with five trials before opting out. This child's data was retained in the analysis, however, as their scores to that point indicated that they had a good understanding of how the device was operated and their performance on the learning phases had indicated that they were able to use the device well. Their opting out was due to some difficulties sustaining attention and focus on the task, which is discussed further below. Scores for the group were converted to percentages to acknowledge the differing numbers of trials with which children engaged.

Statistical analysis was not possible given the small number of children remaining in the study. Instead, a scatter plot was produced (Figure 65) to provide a visual representation of any relationship between children's language understanding and their percentage score on the baseline phase. Examination of this plot indicated that there was no obvious visible relationship between these sets of scores.
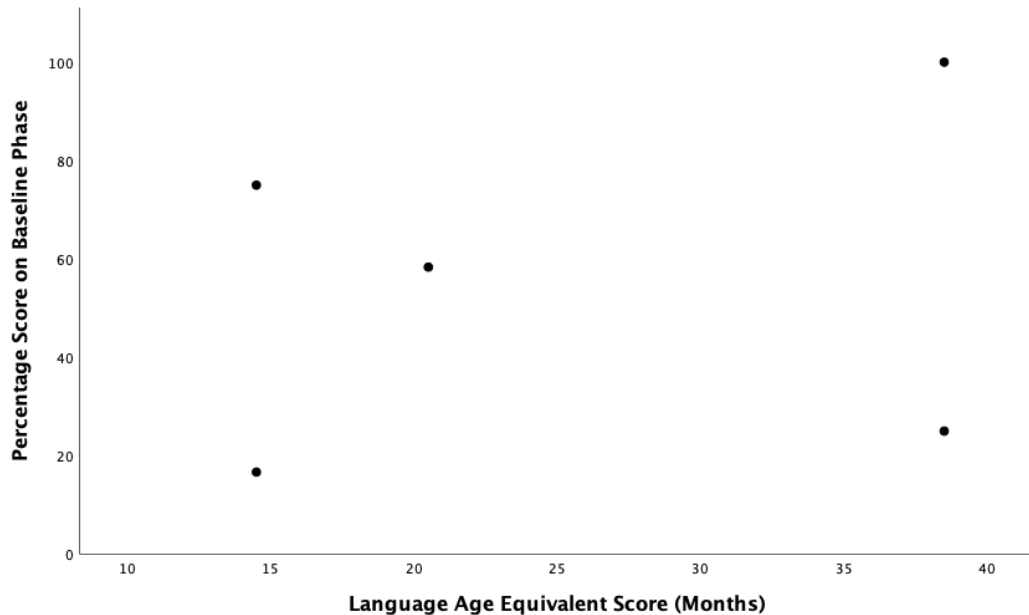
Figure 65 - Scatter plot showing children's language understanding age equivalent plotted against their percentage score on the baseline task.

Of interest here is the observation that children with good functional gaze control (*n* = 4) had a mean percentage score of 64.6%. This was in contrast to the one remaining child from the group with poor functional gaze control, who scored 16.6%.

12.5.8 Intervention Phase

Following the baseline phase, all remaining children (*n* = 5) took part in the intervention phase where causal language instruction was used to support their performance with the device. The one remaining child from the poor functional gaze control group was not able to engage with any of the trials in the intervention phase, not attending to the screen and not following the instructions or causal language prompts given by the researcher. The remaining analysis therefore deals only with children who are in the good functional gaze control group (*n* = 4).

During the intervention phase, all four children completed all six trials with the help of causal language instruction, pointing to the screen and increased verbal feedback. All these children achieved a score of 100% during intervention. Whilst the intervention phase was not timed, it was recorded in the field notes that children required different levels of support to remain engaged with the task and therefore the intervention phase took notably longer for some children than for others.
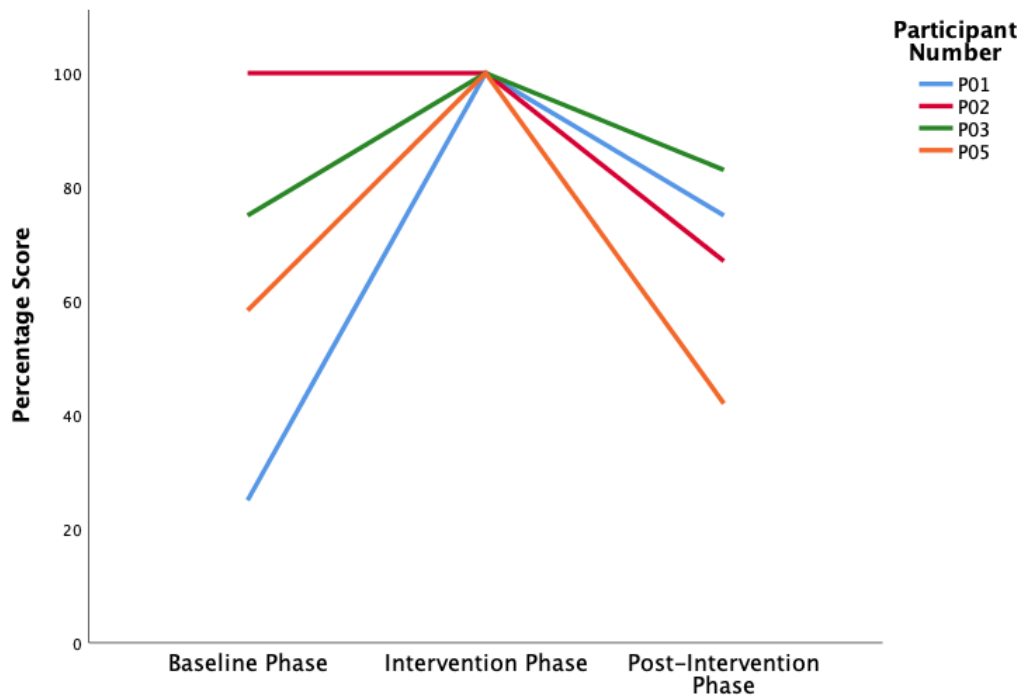
Figure 66 - Performance of children completing all three phases (*n* = 4)

12.5.9 Post-Intervention Phase

As with the baseline phase, the remaining children (*n* = 4) were shown all 12 trials in the post-intervention phase. As in the baseline condition, the same child (P02) was not able to complete all trials, engaging with only six before opting out. Once again, due to her performance on the previous two phases, this child's scores were retained and scores for the group were converted to percentages.

Whilst statistical analysis of this data was not indicated due to the small number of children involved, comparison of means and graphing of the results (Figure 66) indicated that there was very little difference between baseline (M_{score} = 64.58%, SD = 31.46) and post-intervention (M_{score} = 66.75%, SD = 17.745) percentage scores for children who completed all

phases of the activity. It should be reiterated that all of these children were assessed to have good functional gaze control skills.

12.5.10 Attrition

Attrition for children classified as having good and poor functional gaze control is presented in Figure 67, below. Notably, only one child from the good functional gaze control skills group failed to complete the full protocol, and this was the child (P08) who refused to participate any further following technical difficulties with the equipment. By contrast, no children from the poor functional gaze control group completed the full protocol, with no child from this group proceeding further than the baseline phase.
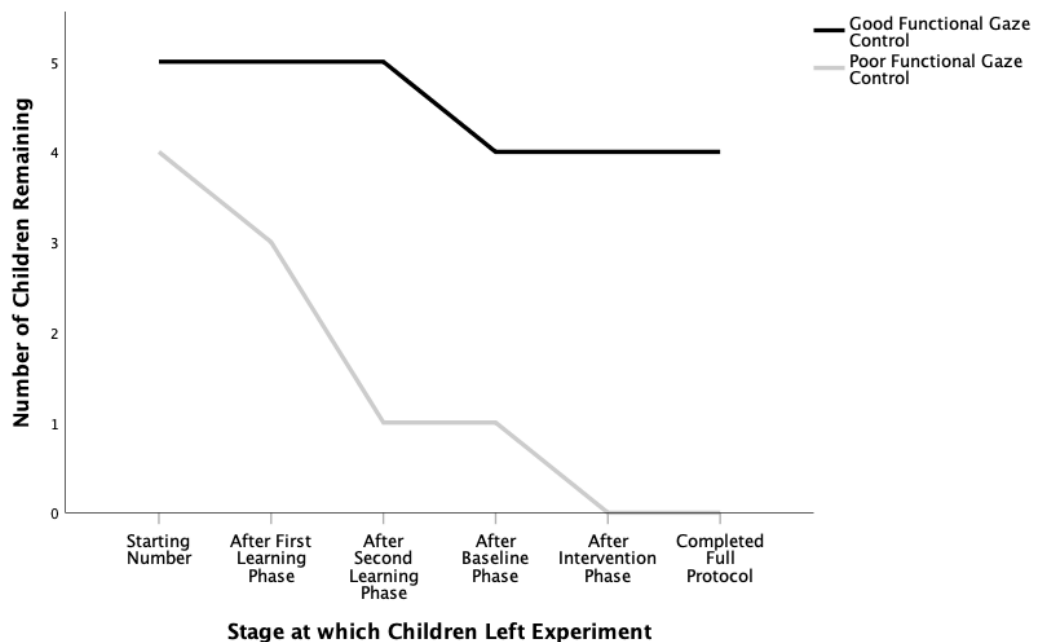
Figure 67 - Line graph showing the rates of attrition for children in both the groups

A further explanation for this pattern of performance could be developmental level (based on level of language understanding). However, two children (P03 and P05) who presented with language age equivalent below 24 months were able to complete the full protocol suggesting that functional gaze control had a stronger relationship with attrition than developmental age.

12.6 Discussion

This final experimental chapter addressed the following research questions:

1. What is the relationship between functional vision skills and performance with eye-gaze technology in children with CP?

2. What is the relationship between developmental age and performance with eye-gaze technology in children with CP?

3. What impact does explicit teaching and prompting have on the performance of this group, and can any improvement in performance be retained?

Given the small number of children recruited to the study, and the high dropout rate during the protocol, statistical analysis was not feasible. This discussion therefore highlights points of interest from the findings in order to address the above questions. The first point of note that four children (P03, P05, P06, P07) had language scores which indicated that their developmental levels were below 24 months. Two of these children (P03 and P05) were able to engage in the full protocol. A more detailed examination of the children in this group is therefore included below.

P03 has one of the lowest language age equivalents in the group (12 – 17 months). Since he was the oldest child in the group (119 months), this would suggest a severe learning disability. Despite this, review of his scores and of the field notes reveals him to be one of the most consistent performers across the baseline, intervention and post-intervention phases. He scored highly on the *FunVis* task, only having difficulty with the visual tracking exercise. He was unwilling to engage in the language assessment beyond the first few items and it was reported by the adult accompanying him that this is a general pattern. This lack of compliance with language testing suggests that his documented level of language learning may be artificially low however this is difficult to corroborate. One possible explanation for his profile of performance given his level of language comprehension is related to his good functional gaze control skills and previous exposure to eye-gaze technology, which had been provided to him with independent funding. As such, use of eye-control technology was not a novel activity for P03 as it was for typically developing children.

P05's language age equivalent was established at between 18 – 23 months, that is approaching the age at which typically developing children showed improved performance on eye-control tasks. Review of the field notes indicated that, whilst she achieved the same *FunVis* score as P03, note was made that some of the skills demonstrated were somewhat reduced in quality: with greater latency on both the single item fixation and the gaze switching tasks. This may explain why her scores on the baseline and post-intervention phases are lower than P03. Written observations noted that she required more support and prompting in the intervention phase. P05 also had prior exposure to eye-gaze, having been provided with a multi-page language system in a communication software package with 15 items per page, with which some good progress was reported to be being made.

For these two children, having good functional gaze control skills and prior exposure to eye-gaze technology appeared to help them participate and perform well in the tasks, even though their language level was below the 22 months at which typically developing children engaged. It is worth reiterating at this stage that the tasks here had been designed to be administered, at least in the baseline phase, without the need for understanding of language or instructions from the researcher/ It should also be noted that, for all children in the typically developing group, the activity was novel, whereas these two children had previously made use of similar skills to access their own eye-gaze devices. Their performance, even at baseline, was better than the group average for typically developing children.

Notably, P06 and P07 also had language levels in the 12 – 17 month range, as well as previous experience with eye-gaze technology, but both scored poorly on the *FunVis* indicating marked difficulties with functional gaze control. P07 in particular was not able to score on any of the *FunVis* items, failing to fix on the stimuli at any point during the session. This performance was reflected by his performance with the eye-gaze system. He was not able to calibrate the device and subsequently could not fixate on any items on the learning phase. When staff were asked about this child's previous eye-gaze use, it was reported that he was using one of the eye-gaze learning packages discussed in this thesis, but that "cameras have struggled to pick up or track his eyes" and they were unsure about the benefits of continuing with this. Finally, P06 presents an interesting case, since he could only demonstrate single item fixation on the *FunVis* screening, not being able to switch gaze or track a moving stimulus. Again, performance on the eye-gaze measure reflected this: he was able to

calibrate and then to perform well on the learning phase (9/12, 75%) where only single item fixation was required. However, on the baseline phase where gaze switching or inhibition of the ineffective stimulus was required, he was not able to score on any of the trials.

Taken together, these results begin to address the first research question. The profiles and subsequent performance of these children suggest that, whilst practice with an eye-gaze system may well be advantageous, well established functional gaze control skills do appear to provide a solid base from which to build. Where children had very low levels of language understanding or severe learning difficulties, having good functional gaze control skills and the opportunity to practice with the technology did seem to provide them with an advantage when it came to participation in these tasks. It was not possible to quantify the amount and types of practice or training that these children had been exposed to previously, however it is interesting to note that the types of activities they were reported as doing, and how well they were reported to be preforming in these, did seem to align with their performance on the tasks included in this experiment.

This supports the idea expressed at the opening of this thesis that there is no reason to suggest that children with low developmental levels should not be considered for eye-gaze, however a solid understanding of their underlying skills will help manage the expectations around how they might perform.

It is interesting to observe the patterns of performance of the two children (P01 and P02) who both had good functional gaze control skills, no previous experience with eye-gaze technology and language understanding in the range from 36 – 41 months. In essence, this makes them the most similar in profile to the typically developing children, since they were similar in developmental age and also engaging with a novel activity.

To examine this further, the performance of these two children was plotted against the two closest equivalent children from the experiments recorded in Chapter 9 (Figure 68). These children (TD03 and TD11) had ages (both 35 months) which were most similar to the age ranges of the children with CP (36 – 41 months). All children are above the 32-month level where previous results suggest that children are able to make use of eye-gaze technology with minimal support.
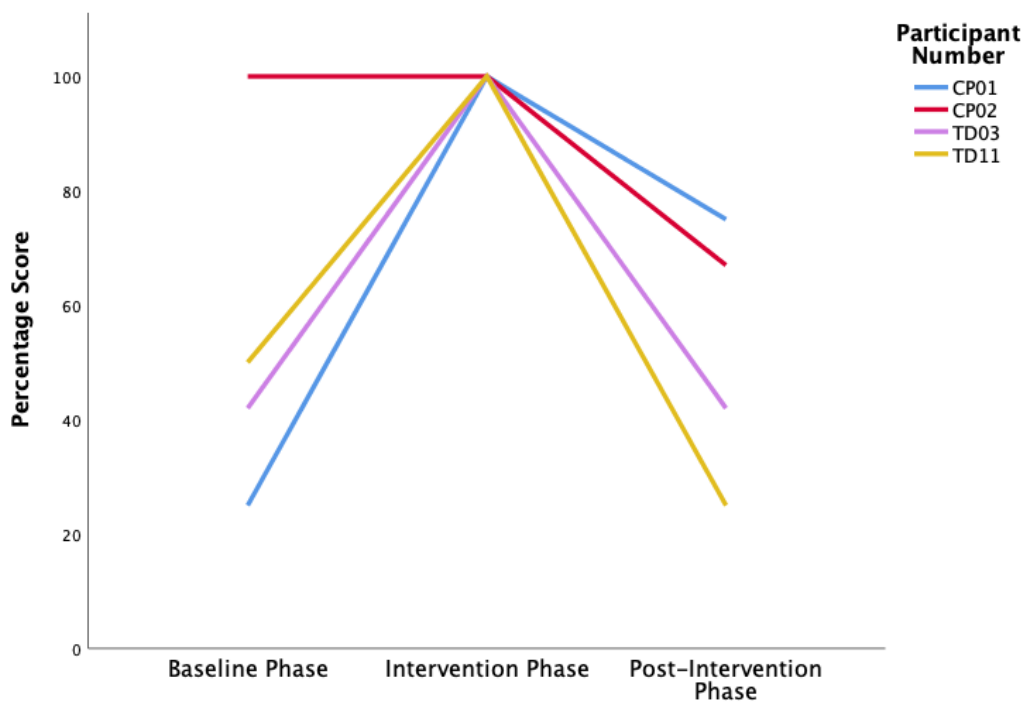
Figure 68 - Comparison of performance between children with CP (CP01 and CP02) and typically developing children (TD03 TD11)

The typically developing children initially perform at a level which falls in between the performance of their peers with CP, but after the intervention perform below both of them. Review of the field notes suggest that both children whose scores decreased in the post-intervention phase required considerable prompting to refocus them to the task. This may suggest that, whilst both of these children were able to use the device, other factors impacted on their performance. Whilst the small numbers and the lack of an exact age match make any interpretation speculative, these findings may suggest that the patterns of performance of the children with CP who have good functional gaze control skills and their typically developing peers are similar, once they reach a developmental level where they are able to work out how the eye-gaze device is controlled. Once they have sufficient understanding of how the device works, it is possible that developmental level will be more useful in determining the types of activities for which they are using the eye-gaze device.

The third research question explores the impact of teaching and prompting on children's performance. Once again, children showed a large improvement in their performance on the task when intensively scaffolded by the researcher, each achieving performance rates of

100%. However, once this scaffolding was removed, the mean scores for the group regressed to baseline levels. The answer to the third research question is therefore that teaching and prompting had an immediate, positive impact on the performance of this group, but that this performance increase is not retained. Performance in the post-intervention phase shows a similar pattern of variability to that seen in the baseline phase. For two children (P01 and P03) there was an increase in performance following the intervention phase. P01 was the participant who showed the greatest gains from baseline (25%) to post-intervention (75%) scores. Reviewing the notes, it was observed that he had engaged well with the intervention, paying good attention to the instructions provided and completing all tasks well, responding with vocalisations to confirm understanding. His performance increased three-fold following the intervention. Similarly, P02 was the only participant to score 5/5 on the FunVis. Review of the notes, as discussed above, revealed that she had difficulties maintaining attention during the task – engaging with a reduced number of trials on both the baseline and post-intervention phase. As with P01, she benefited greatly from the intervention, although this was for different reasons. During the intervention phase, her attention was much more focused, as evidenced by her engagement and subsequent scoring in 6/6 trials during this phase. Although it was not as marked as in the typically developing children, the performance of both these children dipped after the supports of the intervention phase were removed.

For two other children (P02 and P05) performance levels in fact went down following the teaching intervention. This may have been due to a number of factors such as fatigue or becoming tired of repeating the activity. It is worth noting that the scoring system used in this task meant that getting only one or two more correct selections would have returned these children to their baseline scores, or even higher. Therefore, whilst the intervention had an immediate impact, the increase in performance was not carried over, which raises the question of whether the teaching itself had an impact, or whether the act of the researcher focusing the child's attention to the task more actively meant that they engaged better and therefore demonstrated better skills.

12.7 Conclusion

This round of experiments has demonstrated that there is a disparity in performance between children with "good" functional gaze control skills and those with "poor" functional gaze skills. These groups, as defined by children's scores on the *FunVis* behavioural

assessment of functional vision, performed very differently, in terms of their scores and the amount of the protocol they completed.

From the results and discussion above, it is possible to say that it is likely there is some impact of functional gaze control skills on performance, with children who can demonstrate better skills on a behavioural measure performing better on the eye-gaze tasks. This seems to be the case irrespective of previous experience, with children who had made use of eye-gaze devices before but who had poor functional gaze control skills still performing comparatively poorly. Where functional gaze skills were well established, performance seemed to be at a similar level to the typically developing children assessed, although this should be interpreted cautiously as the groups were not matched. This may indicate that children with good functional vision skills are at a developmental advantage when it comes to using eye-gaze technology; already having developed the key skills required to operate the system.

The finding that children with poor functional gaze control skills still struggled with this task even when they had prior experience with eye-gaze technology is an interesting one, given the emphasis placed on practice and repetition by eye-gaze teaching and learning software programmes. The efficacy of this approach may be questioned in light of the children with poor functional gaze control skills who have previously practiced on such games still appearing to struggle with this task. Again, it is important to acknowledge that the numbers here are small and this may be an area for future, more in-depth investigation.

Another interesting finding is that, although all children included in the experiment were able to demonstrate an understanding of cause and effect with physical objects, there was still variation in how well these children were able to determine the causative link between eye movements and control of the device. With the addition of functional gaze control skills as a possible factor in children's performance, what has been shown here is that the acquisition of this causal understanding may be dependent on having these functional vision skills consolidated in order that practice and repetition can help to confirm the connections between cause and effect. This is further discussed in the closing chapter of this thesis.

Taken as a whole, these results underline the importance of functional vision skills to this group of children with CP. Moreover, what they highlight is that these skills should be tested

and understood when clinicians are considering eye-gaze technology. This is discussed further in the concluding chapter, along with ideas for future investigations of the impact of these skills on children's use of eye-gaze technology.

Chapter 13

Discussion and Conclusions

This project has used activities carried out with both typically developing (TD) children and children with cerebral palsy (CP) to investigate the skills needed to control eye-gaze technology.

13.1 Research Aims

The current study aimed to explore factors that may impact on the acquisition of skills required to make purposeful use of eye-gaze control technology. In particular, the research focused on the impact of several factors – developmental age, functional vision and the ability to transfer cause and effect understanding to a new modality – on children's performance in an eye-gaze task. The research is motivated by the emergence of software that makes claims about teaching the core skills needed to make successful use of this technology and a desire to help clinicians make sensible decisions when considering this technology for young children with CP. Throughout the project, the research has been grounded in the established theory, espoused in several models for the selection of assistive technology, that assessment should be based on consideration of the relevant skills of the individual.

13.2 Findings from Typically Developing Children

In the initial stages of this work, several iterations of an experiment to investigate children's understanding of the access method were designed and implemented. The aims of this were to examine at what stage children were able to intuitively infer the causal mechanism needed to control an eye-gaze system and whether or not they could identify the cause and effect relationship between moving their eyes and the resulting actions onscreen. Three experimental rounds were conducted in order to fine tune the design of experimental measures to enable as many children as possible to engage with them.

13.2.1 Engagement

In each round, children's engagement with the activities and their performance was examined. Engagement was defined as being when a child looked at the screen or other test

materials throughout a trial. This may or may not include making a selection. Performance was defined as the number of trials on which they scored – selecting the effective stimulus.

Across the three groups of TD children tested, it was noted that changes in experimental design did allow for greater engagement of younger children. In the initial experiment, no child younger than 24 months showed any engagement with any part of the activity. With subsequent redesigns, children under this age could engage with the tasks, albeit not as well as older children. For example, in the experiments recorded in Chapter 8 where animated stimuli were introduced, children younger than 24 months were able to engage with the learning phases but could not engage with any of the hybrid phase. This was also true for the final round of experiments with the TD group, described in Chapter 9.

Each subsequent redesign of the experiments seemed to enable younger children to engage in more of the protocol. The mean age of the group engaging with the full protocol decreased across the first (M_{age} = 38.00, SD = 5.06), second (M_{age} = 30.3 months, SD = 6.57) and third (M_{age} = 28.67, SD = 4.82) iterations. In all three experimental rounds it was observed that a group of children did not engage at all. Invariably, the group that did not engage contained the youngest children recruited: in the first experimental round (M_{age} = 21.71, SD = 2.69), the second (M_{age} = 21.8 months) and the third (M_{age} = 26.25, SD = 6.13).

Alongside this, a pattern was also noted in the children who completed the full experimental protocol. In each of the three rounds, all children aged 32 months or older were able to engage with the full experimental protocol. This suggests that these children were better able to infer the mechanism by which the eye-gaze device worked. Indeed, in the second experiment (Section 8.5.6, page 173), there was a significant difference in the ages of children who completed one experiment (M_{lang} = 23.23 months, SD = 6.76), and those who completed two (M_{lang} = 30.86 months, SD = 5.84), (t(25) = -3.143, p = .004). There was also a highly significant correlation between language age and the number of trials with which children engaged.

The finding that older children show greater levels of engagement with the tasks is perhaps explained by the developmental literature which describes the maturation of children's attention. Whilst no specific measures of generalised attention were included in this

protocol, the better engagement of older children was consistent with models of attention that show children's distractibility decreases with age (López et al., 2005; Ruff & Capozzoli, 2003) and that the amount of time for which they will attend also increases (Cuevas & Bell, 2014; Ruff & Lawson, 1990). The nature of children's attention also changes, with younger children attending to things to gather information about them and older children deploying their attention to "goal directed tasks" (Ruff & Lawson, 1990).

What these results show is that TD children above 32 months were able to engage well with the activities with minimal support, but that TD children below 24 months struggled to engage. This has relevance to thinking about how eye-gaze technology might be introduced to developmentally younger populations. It is likely that children below this level will require the technology to be introduced in much shorter sessions, with highly motivating activities to maximise their engagement. Indeed, it would be interesting in future work to look at whether providing stimuli that were specifically motivating to each child (a family member, a favourite cartoon character) has any impact on engagement.

13.2.2 Performance

The question of whether or not TD children's performance improved in line with their age is an interesting one. In the first experiment (Section 7.4.4, page 152), it was noted that there was a highly significant, negative correlation between age and the number of trials required to complete the activity, suggesting that older children mastered the task faster. This first experiment had an "open ended" scoring method, where the number of trials it took for children to reach a threshold (six consecutive correct trials) was recorded. As part of the subsequent redesign, the experiments for the second and third rounds were changed to present children with a fixed number of trials and a scoring system based on whether they activated the effective stimulus or performed a different, "incorrect" action. After this redesign, no correlation between age and performance was noted.

Of relevance here is that, even after the task had been redesigned and younger children were better able to engage with it, children below 24 months were only rarely able to progress past the learning phases. This suggests that, even when younger children are able to engage with the activity, they still had difficulties in inferring for themselves how to complete it. In the background sections of this thesis it was discussed that the causal relationship needed

for control of eye-gaze has two components: the understanding that there is a cause and effect relationship between eye movement and the resulting actions on the device and the ability to employ that knowledge to complete a task. Results obtained in this study suggest that older children seem more able to identify the causal relationship between eye movements and control of the device and to then use this for the purpose of controlling the activity.

The performance of this group does seem to suggest that there is a difference in the way in which cause and effect presents in eye-gaze technology. In all the experiments with the TD group, children either demonstrated cause and effect skills with real objects or were of an age where cause and effect understanding could safely be assumed (Sobel & Kirkham, 2006; Yang et al., 2013). However, there was considerable variability when these skills were applied to an eye-gaze task. This was further underscored by the comparison made by administering the same task via a touchscreen. Children performed significantly better (Section 9.7.5, page 200) when using this access method, even though it had been modified to include an unfamiliar delay in activation.

Whilst the likelihood that TD children will already have been familiar with a touchscreen cannot be ignored, the results from this comparison task are consistent with the theories outlined in the background section of this thesis that children are better able to comprehend and make use of an access method when there is minimal spatial dislocation between the input method and the display or feedback (Light & Drager, 2007; Wilkinson & Mitchell, 2014). More generally, the better performance of TD children when using the touchscreen aligns with other findings in the published literature: that cause and effect relationships that are not spatially contiguous are harder to infer or learn (Kushnir & Gopnik, 2007) and that children have a preference bias towards cause and effect relationships which are spatially contiguous (Bonawitz et al., 2010). The high number of TD children preferring to touch the screen in the second experiment (Section 9.7.7, page 202), even when this had no effect, also supports the idea that children have a preference for causal activities where the contingency is physical, visible and cognitively transparent (Bonawitz et al., 2010; Schlottmann, 2001).

13.2.3 Generalisation

Although only tested once during these tasks, the results of the generalisation task included in Chapter 8 (Section 8.5.10 Page 177) warrant a mention here. These results showed that a group of children who completed the full experimental protocol (two learning phases and a hybrid phase, repeated twice with different stimuli) were all able to generalise their learning to "less interesting" stimuli without the need for a new learning phase, performing at a similar level to the initial tasks. Being able to apply that learning to a different scenario is suggestive of children's having fully acquired the causal relationship by which the device operates. It is worth noting that these children were amongst the oldest children tested and were all above 32 months, further supporting the idea that children above this level are able to learn and apply the causal mechanisms by which the eye-gaze device operates.

13.3 Findings from Children with Cerebral Palsy

Once the experimental measures had been designed and refined with three groups of TD children, they were then used to test the clinical population who are the focus of this research: children with CP. However, since the background chapters have demonstrated that this group of children often present with one or more comorbid impairments, it was decided to investigate the impact of one of these in particular: functional vision.

13.3.1 Functional Vision Skills

The aim of exploring this was to find out what impact children's functional vision skills had on their performance with an eye-gaze system. Chapter 12 showed that children with comparatively poor functional gaze control skills, as assessed by a simple screening tool, were not able to use their vision to complete the eye-gaze activities (Section 12.5.10, page 268). The patterns of performance of the two groups of children may indicate that children with better functional gaze control skills are at a developmental advantage when it comes to the use of eye-gaze technology. Being able to use vision functionally to fixate and switch gaze between objects may provide these children with a solid foundation from which to build when learning to use eye-gaze technology. Not needing to learn these skills at the same time as learning to use the technology may mean that they are better equipped to explore how it works and what they can do with it.

Children's performance on the behavioural fixation task (Section 11.5.6, page 244) suggested that there was a statistically significant relationship between children's developmental level (as assessed through their language age) and their performance on a fixation task. This suggests that there may be a relationship between developmental level and functional vision skills that might impact on children's performance. There is also the finding about children's previous experience with eye-gaze to be taken into account. In the group with good functional gaze control skills, even developmentally younger children performed comparatively well on the eye-gaze task when they had previous experience of the technology. In the group with poor functional vision skills, children performed poorly on the eye-gaze tasks, whether or not they had prior experience with a similar system. This may be suggestive of a cumulative deficit, where children with poor functional vision skills are not then able to use their vision to explore the technology, learn the mechanisms by which it works and subsequently improve their skills.

Understanding the functional vision skills of children with CP does, then, seem to hold some promise in determining their likely performance with eye-gaze technology. For clinicians considering the use of this technology with children on their caseload, the inclusion of a measure of functional vision in their assessment may well be helpful. Both the Matching Person and Technology (MPT) model and the Human, Activity, Assistive Technology (HAAT) model advocate for assessment to be based on a sound understanding of an individual's strengths and difficulties, which should underpin the selection of interventions. The recommendation that children's functional vision should be assessed when considering eye-gaze technology is consistent with this.

13.3.2 Testing Functional Vision

Findings such as these contribute to the growing body of literature about the importance of measuring visual function in children with CP. It has been proposed that good functional vision cannot and should not be assumed (Sargent et al., 2013) in this clinical population and these results underline the importance of understanding these skills for access to technology as well as for communication.

The comparison of functional vision screening methods carried out in Chapter 11 indicates that these skills can be elicited and assessed through simple, behavioural measures. These

offer distinct advantages over the use of eye tracking technology in the assessment of these skills: both in terms of their practicality and the relatively high rate of attrition that the technological approach seemed to entail. The findings of this chapter highlight the potential for simple, easily administered and freely available tools to be deployed by non-vison specialists to gain insight into children's looking behaviours and to factor this into their clinical decision-making around the selection of eye-gaze technology.

13.3.3 Engagement and Performance of Children with CP on Eye-Gaze Tasks

For the children with good functional vision who were able to make use of the eye-gaze tasks, some variation in performance was noted. Again, all of these children had demonstrated an understanding of cause and effect with real objects. Even when the trigger (switch) was spatially dislocated from the item it controlled (toy), all children were able to demonstrate that they understood the mechanisms involved in activating the toy. However, when faced with inferring the causal link between eye movements and control, some children still appeared to have difficulties. For children with CP, engagement with the task was at a similar level to the TD group. What is notable is that some children performed better than children in the TD group, although children were not age-matched in these experiments.

13.4 Teaching

This thesis has also explored the impact of teaching on children's performance with eye-gaze technology. As discussed in Chapter 5, giving children instructions is the best strategy available when it comes to teaching eye-gaze technology, since it is not easy to model or otherwise demonstrate to children. This was therefore the approach adopted for the teaching interventions described in this thesis. A causal language approach was adopted, since this has been shown to have value when teaching non-spatially contiguous relationships (Bonawitz et al., 2010).

The impact of teaching was explored in both the TD and CP children. In both cases the pattern was the same: children moved from a baseline score to a very high level of performance during the intervention phase, but then regressed to levels similar to their baseline in the post-intervention phase. In these experiments, the impact of explicit teaching appeared negligible, although it should be noted that only one, short session took place.

This does, however, raise some questions about exactly which aspects of the teaching were helpful. The performance increase and decrease described above may be indicative of the teaching intervention serving the purpose of focusing children – increasing their engagement with the task by prompting them to re-engage with the activity. Particularly for the group of children with CP, the increase in performance during the teaching session still included some quite significant variation in the quality of their engagement: some children requiring more refocusing to the activity than others and some taking much longer to reach the end of the teaching intervention due to this. Whilst all children were eventually able to engage with and score on six-out-of-six trials, the variation in the amount of support they required to do this cannot and should not be ignored. Therefore, it would be interesting to explore whether there was any specific impact of the "causal language" approach or if the children benefited from the teaching session only through being more engaged with the device.

13.4.1 Eye-Gaze Teaching Software

An initial motivation for this research is the author's clinical experience of the increased use of eye-gaze teaching and training software by families and clinicians. Moreover, the results generated by such software packages were increasingly being used to support requests for funding or to provide evidence of established cause and effect skills or improving access abilities.

Firstly, it is important to consider where these software packages are "pitched". In general, the perception is that they are for the use of developmentally very young children who are first being introduced to eye-gaze technology. The early activities are at a sensory or experiential level, indicating that they are being targeted at developmentally very young children. The claims are often that these activities teach children that they are in control of the camera. Given the findings from both the TD and CP populations, there may be questions around whether developmentally younger children would be able to infer this from the activities on offer. What is interesting, however, is that the sensory or "blank screen engagement" tasks could be used by all children with physiologically intact eyes, irrespective of their functional gaze skills, since they do not involve fixation on targets or any element of moving gaze purposefully between targets. Rather, the software produces animation and sound at any onscreen location where the child's gaze point is registered.

This leads to the second question about the use of such software. The packages place a great emphasis on practice, encouraging the repetition of activities to hone and train the skills being targeted. However, the results of the final round of experiments suggest that even those children who had prior experience with eye-gaze systems did not perform well on these tasks if they had poorly developed functional gaze control skills. What is being demonstrated by the results here is that practice may be of limited benefit for this group of children, or that progress made with eye-gaze technology may be much slower. Returning to the literature base, the longitudinal study by Borgestig and colleagues is worth revisiting here. In that study (Borgestig et al., 2015), progress made by children with movement disorders seemed to be slow, with gains made in specific areas (accuracy and speed of reaction to the onset of a target) over a relatively long time period with frequent intervention. It is beyond the scope of this work to say whether such slow progress would be considered "worth" the considerable investment of time, but it would raise legitimate questions about whether eye-gaze is the most appropriate way for these children to access assistive technology or whether they might better be supported in another way. As Gosnell, Costello and Shane (2011) espouse: "Surely, the greatest harm of a faulty clinical decision is the time wasted learning or attempting to learn to use an inappropriate […] technology" (Gosnell, Costello, & Shane, 2011, p. 87).

Another question is how clinicians can be sure that the eye-gaze teaching software is in fact teaching or testing the skills claimed. Mention has been made earlier of software confusing "cause and effect" with "preferential looking"; where a child's looking to an item which instantly reacts to their gaze is reported as demonstrating an understanding of causation. This work has demonstrated that it is important for clinicians to take a "task analysis" approach to these software packages, applying critical thinking to their use and observing children's engagement and performance on the activities for themselves.

The paradigm advocated by eye-gaze teaching software is one of progression through a continuum of skills. This continuum might start with early sensory interactions and progress through a variety of "stages" towards the use of a device for a particular function such as communication or computer control. Whilst we have already discussed that these stages or levels are perhaps arbitrary, it is worth making another point about what the findings in this thesis might mean for such continuums of learning. Setting aside momentarily the

aforementioned difficulties that some children may have in mastering these skills, what has been demonstrated here is that children can still present with considerable variability within each skill area – which may lead to their being "moved on" through the levels too quickly before they have properly consolidated the skill. To elaborate: where an algorithm is tasked with determining whether or not a child has established a skill, this can only be done by identifying when performance crosses a particular threshold. Considering the questions about which skill is being tested, the support offered by the software, the possibility that a child might (through the Midas Touch problem) complete an activation by accident and the general variability of performance noted in several of these experiments, it is entirely possible that children may be recorded as having "established" a skill purely because they crossed said threshold. This might lead to children being moved on too soon and could result in considerable frustration.

An extension of this is the introduction of "communication" activities into many teaching packages. It is beyond the scope of this work to delve too deeply into this, but it is reasonable to say that the inclusion of such elements can lead to the perception that these skills are all part of the same continuum. Once again, this may elevate the expectations of families and professionals. In a similar fashion to the Gosnell, Costello and Shane paper cited above, the paper by Griffiths and Price (2011) that provided a large part of the motivation for this research warns of the risks of missing opportunities for technology to support a child at an appropriate level because the expectation is that they are working towards a much larger and possibly very difficult goal (Griffiths & Price, 2011).

As stated at the outset, there is nothing particularly "wrong" about use of eye-gaze teaching software or the activities therein. Whilst the activities contained in eye-gaze training packages may be helpful tools to assess children, clinicians should be cautious about interpreting the results, particularly when the mechanisms by which those results are obtained are not made clear. Equally, the use of eye-gaze technology as a device for promoting independent play and leisure for developmentally young children with movement disorders is an important one and should not be undervalued.

13.5 Limitations

It should be acknowledged that the final activities were carried out with only a small group of children and that the nature of the opportunity sampling method means that they were not a homogenous group. Whilst this may be considered a limitation, it should also be highlighted that this is not unusual; Karlsson and colleagues (2018) in the conclusion of their systematic review highlight that this is often the case with assistive technology studies, and particularly those involving eye-gaze, since finding homogeneous groups of participants requires "including the physical and intellectual abilities of the user, the purposes for which the technology is required, the type of hardware and software which will be appropriate and the nature of the outcomes to be measured" (Karlsson, Allsop, Dee-Price, & Wallen, 2018, p. 503).

The impact of children's attention was not explored in these experiments. Particularly in the groups of TD children, there was considerable variation in the number of trials for which they engaged with the activity. The results of Chapter 9 in particular, where the reasons for children's failing to score on each trial were quantified (Section 9.7.7, page 202), raise questions about whether attention might play a part in determining engagement and performance. A measure of children's general attention could be included in future studies to address this. In addition, as suggested above, the effect of tailoring the stimuli to each child is something that might be explored in future studies.

The fact that children were each seen for one or two sessions only is another potential limitation, along with the relatively short intervention phase. The performance of the group with CP, for whom the intervention phase sometimes took a considerable time due to the need to focus them on the activity, suggests that longer intervention sessions may not be appropriate for all children. However, providing some children with more exposure to the intervention may be useful. Further work is needed to examine the impact of longer-term practice on performance with eye-gaze technology. Similarly, the effect of teaching and training could be assessed over longer time periods. As with the group size above, it should be noted that the need for more longitudinal studies is well-established in the fields of assistive technology and AAC.

Another potential limitation is the use of dwell selection. During the experiments described here, children were not explicitly taught to dwell in order to make a selection. This was a conscious decision to avoid aspects of the Midas Touch problem as described in Chapter 5. However, it could be argued that some element of training children to use the dwell selection task may have been helpful. Since dwelling is very similar in nature to fixation, it is debatable whether this would have had any impact on the performance of the group of children with poor functional gaze control skills.

13.6 Summary

What has emerged from this work is that there appears to be a complex interplay between children's developmental level and functional gaze control skills which appears to be reflected in how well children with CP perform in eye-gaze tasks:

- Where these children were developmentally above 22 months and had good functional gaze control skills, they performed well on tasks using the eye-gaze device, regardless of whether they had previously used one.
- Where children were at or below the 22-month level but had good functional gaze control skills, they demonstrated similarly good levels of performance if they had previously practiced with to an eye-gaze system.
- Where children had poorly developed functional gaze control skills, they performed poorly on these tasks, regardless of previous experience with eye-gaze.

Taken together, this appears to suggest that there is some interplay between developmental age, functional vision skills and previous experience. However, the impact of functional gaze control skills is seemingly the most important. Having well developed functional vision skills means children already have the key building blocks of fixation and gaze switching that are important components of purposeful control of an eye-gaze system.

Ensuring that children's functional vision skills and developmental levels are properly understood before making choices about technology is consistent with established models of assessment and provision of assistive technology.

Whilst use of an eye-gaze device should not be ruled out for these children, it is important to understand the impact of poor functional gaze control skills and lower developmental levels to acknowledge that progress may be slow, and that full control of a device may be a challenging target. In common with other interventions recommended for these children, it may be better to seek a way for them to access activities that is less reliant on a skill that is difficult for them. This is again consistent with the general principle outlined in the early sections of this thesis: that use of eye-gaze technology is not a goal in itself, but rather one tool amongst many that may be used to access activities which increase children's participation.

13.7 Clinical Relevance

This research has its roots in the author's clinical experience, and it was always the intention that the outcomes should include recommendations for clinical practice. In the background section of this thesis it was outlined that discussions around eye-gaze technology are often difficult for professionals and families, since the technology has a very powerful allure and can often seem to be a panacea, providing a "simple" access method to technology. Clinical experience suggests that this is not the case, however clinicians lack evidence on which to base these discussions.

The first recommendation for clinical practice is that children being considered for eye-gaze technology should undergo the sort of functional vison screening assessment described in Chapters 11 and 12. The current literature shows that establishing children's functional vision abilities is important (Atkinson et al., 2002), yet it has been shown that these skills are still under-reported by professionals considering assistive technology and AAC (Sargent et al., 2017). Using screening tools such as the *FunVis* in the first instance can support clinicians and professionals in identifying children who may have difficulties with their functional vision or functional gaze control skills. Identification of children who may have difficulties with these skills can prompt professionals to seek the advice of vision specialists or specialist assessment centres familiar with the assessment of vision skills and abilities in this often-complex population. This, in turn, will allow for more open discussion between families and clinicians about the subject of functional vision and its impact on eye-gaze performance. Screening tools such as the *FunVis* fit well with the models discussed in Chapter 2 of this thesis, which

emphasise the importance of a clear understanding of the individual's skills when selecting assistive technology.

Secondly, it is recommended that eye-gaze teaching packages are used carefully by clinicians working with children and that their results are interpreted with caution and not "taken as read". When teaching software is being used, discussion should be entered into with families about their use and what progress is likely to be made. Speaking with families about the skills that are being demonstrated can help to manage expectations around the use of a technology that may appear to hold huge promise. In common with other forms of assistive technology clinicians should frame eye-gaze as a tool with which children can participate in an activity, not as the activity itself. This "targets not tools" approach will also ensure that children's progress with an activity is acknowledged and celebrated, regardless of how it is accomplished.

Thirdly, it has been a consistent finding of the work with both TD and CP children that established cause and effect with physical toys is not sufficient for clinicians to assume that children will be able to effortlessly transfer these skills to controlling an eye-gaze device. The work presented here points to cause and effect with physical objects not being a good predictor of whether or not children will be able to apply these skills to an eye-gaze system, where the skills needed to infer the causal relationships seem to be different.

Finally, the observations and results obtained across this work has provided some pointers for the way in which children are introduced to this technology. For children who are developmentally younger, the introduction of the technology in short, motivating sessions is likely to be more appropriate. It will be important to keep in mind that children's engagement with the task should be monitored in order to ensure that they are given the best possible chance to explore how the technology works. The implementation of the technology in short but regular sessions is consistent with the view of the various stakeholder groups consulted in a recent Delphi study (Karlsson et al., 2020, submitted for publication).

13.8 Future Research

In carrying out this research, several potential areas of further study have come to light. As acknowledged above, the groups taking part in this study are of varying sizes. Although the

groups for the TD experiments and the group of CP children taking part in the experiments to determine how best to measure functional gaze control skills, the group of children participating in the final round of experiments is small by comparison. One possible area for future work is therefore to expand the protocol to a larger group of children. This might include looking at the impact of different subtypes of CP on performance with both functional vision and eye-gaze technology.

One of the questions that remains is whether or not eye-gaze technology can (or should) be used to teach functional gaze control skills where they are absent or improve them where they are weak. Some eye-gaze teaching software packages make claims that they contain activities for children to "practice" or improve different visual skills. An idea for future study would be to examine whether longer-term practice with eye-gaze or behavioural measures has any impact on functional vision skills.

Similarly, it would be interesting to look at whether the cause and effect skills needed to use eye-gaze can be broken down any further than they have been in this experiment. Having observed that cause and effect appears to present differently when applied to eye-gaze technology, it would be interesting to see if children can be in any way "scaffolded" towards a better understanding of the causal relationship between looking at the device and the resulting actions on the screen. One possible way of doing this might be to look at the process of learning to dwell. This is something that is often included in eye-gaze learning packages, but it would be interesting to explore possible ways of doing this, which might include identifying a very low dwell speed – or possibly a "dwell-free" activity – and then steadily increasing this towards a more purposeful dwell selection such as the one included in the experiments in this thesis.

More investigation into generalisation is also something that may be helpful. In order for any skill to be truly functional for children, it should be possible for them to apply it across a range of activities and contexts, and practice is often recommended as part of functional and motivating activities (Karlsson et al., 2020, submitted for publication). Identifying how and if children are able to generalise their skills with eye-gaze technology will answer two important further questions. Firstly, it will ensure that the learning is not simply task-specific if children are able to apply their learned skills to other activities and stimuli. This will help

shed further light on the utility of eye-gaze teaching software, where practice and improvement on the same activities is often interpreted as progress towards a particular skill. This improvement may in fact be a result of increase familiarity with the task and not the mechanisms that underpin it, and this would be useful to explore in more detail. Secondly, it would help provide insight into how eye-gaze can be used to access a range of different activities. Several times in this work the inclusion of choice-making or communication activities in eye-gaze teaching software has been discussed and questioned. However, it is recognised that the cognitive load of an access method is reduced as it becomes more familiar, as automaticity develops and the need for effortful control over performance decreases (Griffiths & Addison, 2017). Thus, it would be helpful to look at the impact of experience with eye-gaze on performance in a range of tasks and how children can readily transfer communicative ability demonstrated through other means to an eye-gaze system.

As alluded to earlier, the impact of teaching is something that may be interesting to investigate further. Verbal instruction still appears to be the best way to support children in learning to use this technology, but these experiments have not compared different methods of teaching and instruction. It would be useful to compare, for example, whether causal language instruction has any advantage over other methods of instruction. It is not clear from the findings of this study whether there is any intrinsic value in the content of the teaching intervention, or whether the act of refocusing the children to the task is what results in their improved performance. As discussed above, it would seem important that longitudinal study designs are used to assess the impact of teaching and training on performance in eye-gaze tasks.

13.9 Conclusion

The research presented here takes as its starting point the idea that no child should be denied access to any particular assistive technology, nor that a return to candidacy models and prerequisites is helpful. The research is built on the same foundations as many assistive technology selection and implementation frameworks: that robust understanding of a person's strengths and needs should be placed at the centre of assessment. What is proposed by this research is that understanding a child's developmental profile and, in particular, aspects of their cognition and use of vision, gives helpful information to clinicians needing to make decisions about the use of eye-gaze technology for children with CP. Some children, it

is proposed, may be at a "developmental advantage" if their functional vision and cognitive skills are more developed. That is not to say that children with weaker skills in these areas cannot make progress. Rather, the outcomes of this research may be used to manage the expectations of professionals and families around this complex and often alluring technology.

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Appendices
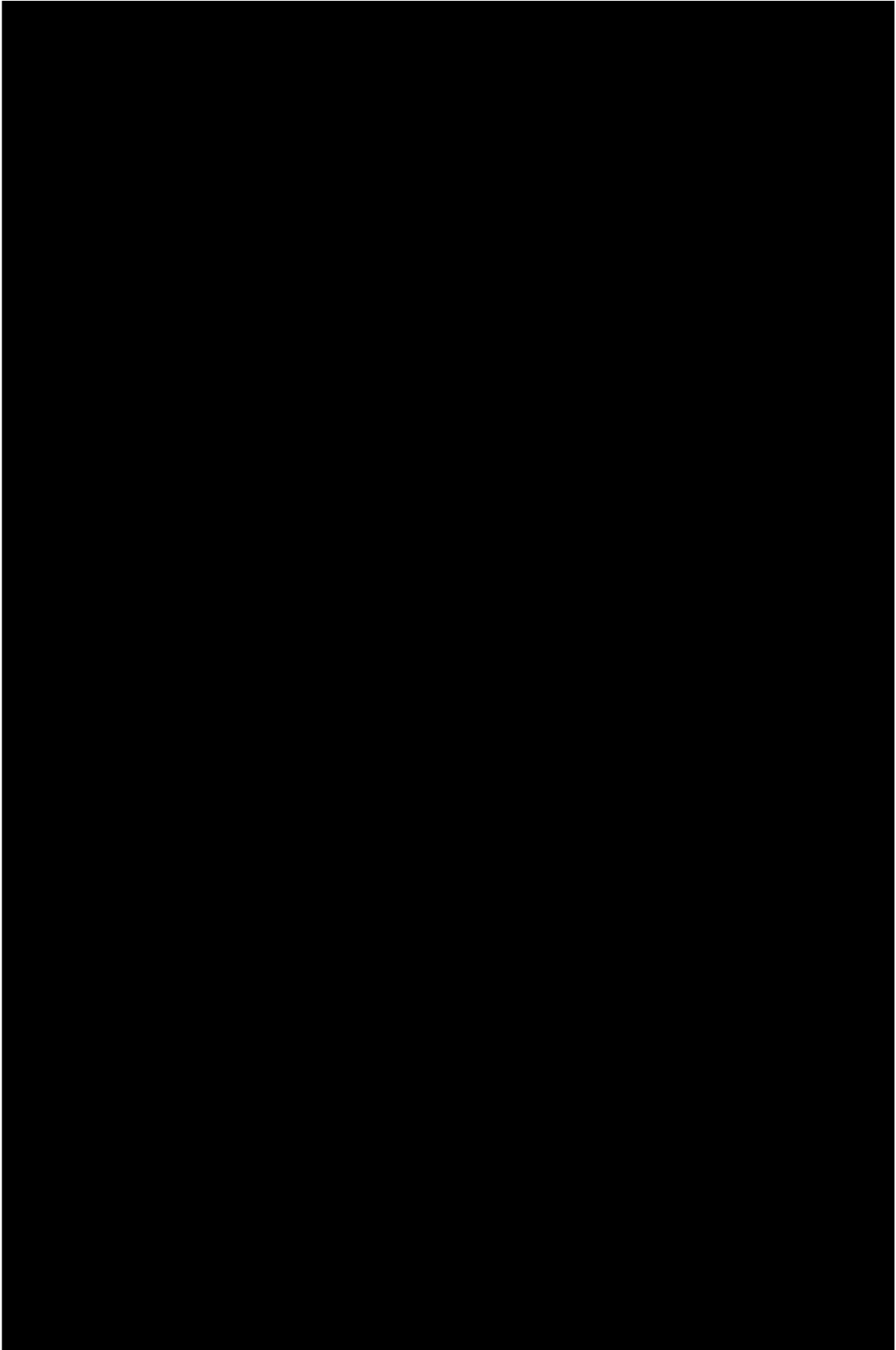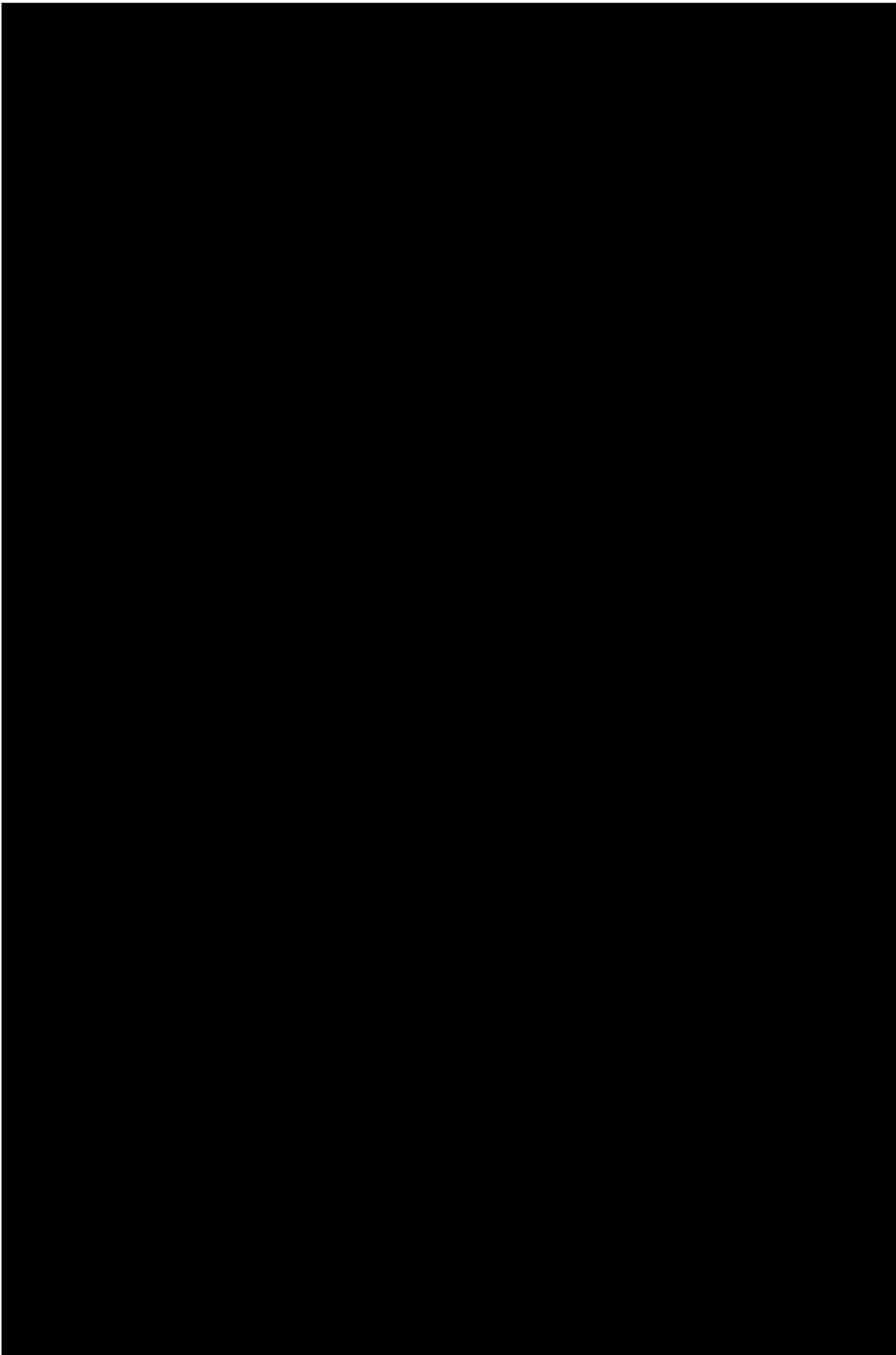
Appendix B-1 Ethics Application

IMPORTANT: ALL FIELDS **MUST** BE COMPLETED. THE FORM SHOULD BE COMPLETED IN PLAIN ENGLISH UNDERSTANDABLE TO LAY COMMITTEE MEMBERS.

SEE <u>NOTES IN STATUS BAR</u> FOR ADVICE ON COMPLETING EACH FIELD. YOU SHOULD READ THE ETHICS APPLICATION GUIDELINES AND HAVE THEM AVAILABLE AS YOU COMPLETE THIS FORM.

APPLICATION FORM

SECTION A	APPLICATION DETAILS

A1 — **Project Title:** Developmental pre-requisites for use of eye control technology

Date of Submission: August 2014	Proposed Start Date: 01 October 2014
UCL Ethics Project ID Number: 1328/006	Proposed End Date: 01 October 2015

If this is an application for classroom research as distinct from independent study courses, please provide the following additional details:

Course Title:	Course Number:

A2 — **Principal Researcher**

Please note that a student – undergraduate, postgraduate or research postgraduate cannot be the Principal Researcher for Ethics purposes.

Full Name: Dr Michael Clarke	Position Held: Senior Lecturer
Address: Room 202b Chandler House, 2 Wakefield Street, London, WC1N 1PF	Email: ▮▮▮▮▮▮
	Telephone: ▮▮▮▮▮▮
	Fax:

Declaration To be Signed by the Principal Researcher

- I have met with and advised the student on the ethical aspects of this project design *(applicable only if the Principal Researcher is not also the Applicant)*.

- I understand that it is a UCL requirement for both students & staff researchers to undergo Disclosure and Barring Service (DBS) Checks when working in controlled or regulated activity with children, young people or vulnerable adults. The required DBS Check Disclosure Number(s) is: Dr Michael Clarke: 001405941272; Emily Upton, 001332247420; Tom Griffiths: 001451015534;

- I have obtained approval from the UCL Data Protection Officer stating that the research project is compliant with the Data Protection Act 1998. My Data Protection Registration Number is: This project uses anonymised data do not have to be registered with the Data Protection Team.

- I am satisfied that the research complies with current professional, departmental and university guidelines including UCL's Risk Assessment Procedures and insurance arrangements.

- I undertake to complete and submit the 'Continuing Review Approval Form' on an annual basis to the UCL Research Ethics Committee.

- I will ensure that changes in approved research protocols are reported promptly and are not initiated without approval by the UCL Research Ethics Committee, except when necessary to eliminate apparent immediate hazards to the participant.

- I will ensure that all adverse or unforeseen problems arising from the research project are reported in a timely fashion to the UCL Research Ethics Committee.

- I will undertake to provide notification when the study is complete and if it fails to start or is abandoned.

SIGNATURE: **DATE:**

A3	Applicant(s) Details *(if Applicant is not the Principal Researcher e.g. student details):*

Full Name: Emily Upton

Position Held: Undergraduate Student

Address: Room 202b Chandler House, 2 Wakefield Street, London, WC1N 1PF	Email: ▬▬▬▬▬▬▬
	Telephone:
	Fax:

Full Name: Tom Griffiths

Position Held: Research Student

Address: Room 202 Chandler House, 2 Wakefield Street, London, WC1N 1PF	Email: ▬▬▬▬▬▬▬
	Telephone:
	Fax:

A4	Sponsor/ Other Organisations Involved and Funding

a) **Sponsor:** ☒ UCL ☐ Other institution
If your project is sponsored by an institution other than UCL please provide details:

b) **Other Organisations**: If your study involves another organisation, please provide details. *Evidence that the relevant authority has given permission should be attached or confirmation provided that this will be available upon request.*

c) **Funding:** What are the sources of funding for this study and will the study result in financial payment or payment in kind to the department or College? *If study is funded solely by UCL this should be stated, the section should not be left blank.* The study is funded by UCL

A5	Signature of Head of Department or Chair of the Departmental Ethics Committee *(This must not be the same signature as the Principal Researcher)*

I have discussed this project with the principal researcher who is suitably qualified to carry out this research and I approve it. The project is registered with the UCL Data Protection Officer, a formal signed risk assessment form has been completed, and appropriate insurance arrangements are in place. *Links to details of UCL's policies on data protection, risk assessment, and insurance arrangements can be found at:* http://ethics.grad.ucl.ac.uk/procedures.php

UCL is required by law to ensure that researchers undergo a Disclosure and Barring Service (DBS) Check if their research project puts them in a position of trust with children under 18 or vulnerable adults.

HEAD OF DEPARTMENT TO DELETE BELOW AS APPLICABLE

I am satisfied that checks: (1) have been satisfactorily completed
                                (2) have been initiated
                                (3) are not required

If checks are **not** required please clarify why below.

2

Chair's Action Recommended: ☐ Yes ☒ No

A recommendation for Chair's action can be based only on the criteria of minimal risk as defined in the Terms of Reference of the UCL Research Ethics Committee.

PRINT NAME:

DATE:

SIGNATURE:

SECTION B	DETAILS OF THE PROJECT

B1 | Please provide a brief summary of the project in <u>simple prose</u> outlining the intended value of the project, giving necessary scientific background *(max 500 words)*.

In recent years of eye-control technology has been used increasingly to support people with severe physical disabilities to control technology, such as a personal computer, or speech generating device. Eye-control technology tracks the position of the eyes and allows the user to control a curser on the screen simply through eye movements. The eye-tracking technology uses cameras and infra-red light built into a computer monitor to monitor the user's eye gaze movements There are no wires or physical connections involved. This technology represents a major breakthrough in the support of people with disability and is being recommended for increasingly young children. However, to date, little guidance is available on the developmental skills that children require in order to make best use of the technology provided. Without this guidance families and schools risk disappointment, technological abandonment, and considerable financial loss if/when they purchase eye control technology. This pilot study aims to establish early indicators of developmental age at which the provision of eye control technology may be reasonably considered.

B2 | Briefly characterise in <u>simple prose</u> the research protocol, type of procedure and/or research methodology (e.g. observational, survey research, experimental). Give details of any samples or measurements to be taken *(max 500 words)*.

Research question:
At what developmental age can young children learn to use their gaze behaviour to control technology to perform simple tasks?

Participants:
This cross-sectional project will work with a cohort of 50 typically developing children aged 9 months to 3 years.

Measures/procedures:
They will be presented with eye control technology and simply asked to complete a series of tasks that test their ability to engage with the technology. These centre on the ability to learn and engage with cause and effect activities (e.g. finding and looking at a specific target in order to make a mouse climb stairs to reach a piece of cheese). Children's performance on the activities will be measured by behavioural observation and by automatic recording of their looking behaviour using eye-tracking facilities on the eye-control technology.

The children's development level will be ascertained through the use of well established measures of language (Pre-School Language Scale-5*), and cognition (Mullen Scale of Early Learning**)

Analysis:

An initial investigation of descriptive statistics will be used to characterise performance. Scores gained from children of different developmental ages will be compared.

References:
*Zimmerman, I.L., Steiner, V.G., Evatt Pond, R. Preschool Language Scale, Fourth Edition (PLS-5). London: Pearson; 2002.

**Mullen EM. Mullen scales of early learning. Circle Pines, MN: American Guidance Service.; 1984.

3

	Attach any questionnaires, psychological tests, etc. (a standardised questionnaire does not need to be attached, but please provide the name and details of the questionnaire together with a published reference to its prior usage).

B3	**Where will the study take place (please provide name of institution/department)?**
	If the study is to be carried out overseas, what steps have been taken to secure research and ethical permission in the study country? Is the research compliant with Data Protection legislation in the country concerned or is it compliant with the UK Data Protection Act 1998?
	The study will take place in schools and nurseries.

B4	**Have collaborating departments whose resources will be needed been informed and agreed to participate?**
	Attach any relevant correspondence.
	No collaborating departments, UCL only.

B5	**How will the results be disseminated, including communication of results with research participants?**
	The results will be used in the dissertations of the research students, and disseminated in academic fora. Parents will have the opportunity to receive specific information relating to their child, on request.

B6	**Please outline any ethical issues that might arise from the proposed study and how they are be addressed.** *Please note that all research projects have some ethical considerations so do not leave this section blank.*
	Although the study procedures are not invasive we recognise that it is possible that some children may display distress or anxiety at the presence of researchers or during assessment.
	The research students are experienced in working with children (as clinicians and student speech and language therapists) and will assess the response of the child to study procedures.
	If a child displays anxiety or distress, we will immediately stop procedures and only proceed after a suitable interval, and/or, following guidance from parents or school/nursery staff. We will withdraw children from the study where they demonstrate on-going distress or anxiety

SECTION C	**DETAILS OF PARTICIPANTS**

C1	**Participants to be studied**

C1a. Number of volunteers:	50
Upper age limit:	9 months
Lower age limit:	4 years

C1b. Please justify the age range and sample size:

The project has been designed to be effective in meeting its aims, and achievable within the timeframe available given the reasonable expectations for the research students' commitment to the project.

4

C2 If you are using data or information held by a third party, please explain how you will obtain this. You should confirm that the information has been obtained in accordance with the UK Data Protection Act 1998.

N.A.

C3 Will the research include children or vulnerable adults such as individuals with
a learning disability or cognitive impairment or individuals in a dependent or unequal relationship? ☒ Yes ☐ No

How will you ensure that participants in these groups are competent to give consent to take part in this study? *If you have relevant correspondence, please attach it.*

Parental consent will be obtained and each child's assent to taking part in the activities will be sought at the time of assessment.

C4 Will payment or any other incentive, such as gift service or free services, be made to any research participant?

☐ Yes ☒ No

If yes, please specify the level of payment to be made and/or the source of the funds/gift/free service to be used.

Please justify the payment/other incentive you intend to offer.

C5 Recruitment

(i) Describe how potential participants will be identified:

Local nurseries, schools, early years centres, will be contacted to identify participants.

(ii) Describe how potential participants will be approached:

In the first instance, head teachers, nursery leaders and managers will be contacted as gatekeepers to the participants. Subsequently, parents will be approached (via school or nursery etc.) using the prepared information sheet and consent forms.

(iii) Describe how participants will be recruited:

Children's parents will be approached before approaching the children themselves.

Attach recruitment emails/adverts/webpages. A data protection disclaimer should be included in the text of such literature.

C6 Will the participants participate on a fully voluntary basis? ☒ Yes ☐ No

Will UCL students be involved as participants in the research project? ☐ Yes ☒ No

If yes, care must be taken to ensure that they are recruited in such a way that they do not feel any obligation to a teacher or member of staff to participate.

Please state how you will bring to the attention of the participants their right to withdraw from the study without penalty?

5

C7 | **CONSENT**

Please describe the process you will use when seeking and obtaining consent.

Information sheets and consent forms will be forwarded to children's homes via schools and nurseries. Children will only be approached once signed consent has been received from parents.

A copy of the participant information sheet and consent form must be attached to this application. For your convenience proformas are provided in C10 below. These should be filled in and modified as necessary.

In cases where it is not proposed to obtain the participants informed consent, please explain why below.

C8 | **Will any form of deception be used that raises ethical issues? If so, please explain.**

No deception will be used

C9 | **Will you provide a full debriefing at the end of the data collection phase?** ☒ Yes ☐ No

If 'No', please explain why below.

C10 | **Information Sheets And Consent Forms**

A poorly written Information Sheet(s) and Consent Form(s) that lack clarity and simplicity frequently delay ethics approval of research projects. The wording and content of the Information Sheet and Consent Form must be appropriate to the age and educational level of the research participants and clearly state in simple non-technical language what the participant is agreeing to. Use the active voice e.g. "we will book" rather than "bookings will be made". Refer to participants as "you" and yourself as "I" or "we". An appropriate translation of the Forms should be provided where the first language of the participants is not English. If you have different participant groups you should provide Information Sheets and Consent Forms as appropriate (e.g. one for children and one for parents/guardians) using the templates below. Where children are of a reading age, a written Information Sheet should be provided. When participants cannot read or the use of forms would be inappropriate, a description of the verbal information to be provided should be given. Please ensure that you trial the forms on an age-appropriate person before you submit your application.

6

SECTION D   DETAILS OF RISKS AND BENEFITS TO THE RESEARCHER AND THE RESEARCHED

D1   **Have UCL's Risk Assessment Procedures been followed?**   ☒ Yes   ☐ No

If **No**, please explain.

D2   **Does UCL's insurer need to be notified about your project before insurance cover can be provided?**   ☐ Yes   ☒ No

The insurance for all UCL studies is provided by a commercial insurer. For the majority of studies the cover is automatic. However, for a minority of studies, in certain categories, the insurer requires prior notification of the project before cover can be provided.

If **Yes**, please provide confirmation that the appropriate insurance cover has been agreed. *Please attach your UCL insurance registration form and any related correspondence.*

D3   **Please state briefly any precautions being taken to protect the health and safety of researchers and others associated with the project (as distinct from the research participants).**

The data collection will take place in schools and nurseries. Travel for data collection will be undertaken at normal travel times. The students will be working in classrooms or nursery settings, and typically will have a member of staff present with the children. The research students have considerable experience of working in educational and clinical environments as part of their programmes of study (undergraduate and masters students are undergoing training to be speech and language therapists). All students will be aware of UCL's Speech and Language Therapy Policy for working with (vulnerable) children.

D4   **Will these participants participate in any activities that may be potentially stressful or harmful in connection with this research?**   ☐ Yes   ☒ No

If **Yes**, please describe the nature of the risk or stress and how you will minimise and monitor it.

We are aware that for some children, (albeit rarely in our experience) can display signs of worry or anxiety when working with unfamiliar adults. As noted above, we will constantly monitor the impact of activities on the child and take all necessary action to alleviate any distress displayed.

10

D5 Will group or individual interviews/questionnaires raise any topics or issues that might be sensitive, embarrassing or upsetting for participants?

If **Yes**, please explain how you will deal with this.

N.A.

D6 Please describe any expected benefits to the participant.

There are no direct benefits for parents of typically developing children taking part in the project, but in the long term this early work has strong potential to influence clinical practice, and will inform the field of assistive technology research more generally.

D7 Specify whether the following procedures are involved:

Any invasive procedure(s) ☐ Yes ☒ No

Physical contact ☐ Yes ☒ No

Any procedure(s) that may cause mental distress ☐ Yes ☒ No

Please state briefly any precautions being taken to protect the health and safety of the research participants.

Please note that for some children, working with unfamiliar adults could cause raised anxiety or distress. As noted above, we will constantly monitor the impact of activities on the child and take all necessary action to alleviate any distress displayed.

D8 Does the research involve the use of drugs? ☐ Yes ☒ No

If **Yes**, please name the drug/product and its intended use in the research and then complete Appendix I

Does the project involve the use of genetically modified materials? ☐ Yes ☒ No

If **Yes**, has approval from the Genetic Modification Safety Committee been obtained for work? ☐ Yes ☐ No

If **Yes**, please quote the Genetic Modification Reference Number:

11

D9	Will any non-ionising radiation be used on the research participant(s)? ☐ Yes ☒ No
	If **Yes**, please complete Appendix II.

D10	Are you using a medical device in the UK that is CE-marked and is being used within its product indication? ☐ Yes ☒ No
	If **Yes**, please complete Appendix III.

CHECKLIST

Please submit ether 12 copies (1 original + 11 double sided photocopies) of your completed application form for full committee review or 3 copies (1 original + 2 double sided copies) for chair's action, together with the appropriate supporting documentation from the list below to the UCL Research Ethics Committee Administrator. You should also submit your application form electronically to the Administrator at: ethics@ucl.ac.uk

Documents to be Attached to Application Form (if applicable)	Ticked if attached	Tick if not relevant
Section B: Details of the Project		
• Questionnaire(s) / Psychological Tests	☐	☐
• Relevant correspondence relating to involvement of collaborating department/s and agreed participation in the research.	☐	☐
Section C: Details of Participants		
• Parental/guardian consent form for research involving participants under 18	☐	☐
• Participant/s information sheet	☐	☐
• Participant/s consent form/s	☐	☐
• Advertisement	☐	☐
Section D: Details of Risks and Benefits to the Researcher and the Researched		
• Insurance registration form and related correspondence	☐	☐
Appendix I: Research Involving the Use of Drugs		
• Relevant correspondence relating to agreed arrangements for dispensing with the pharmacy	☐ ☐	
• Written confirmation from the manufacturer that the drug/substance has has been manufactured to GMP	☐	☐
• Proposed volunteer contract	☐	☐
• Full declaration of financial or direct interest	☐	☐
• Copies of certificates: CTA etc…	☐	☐
Appendix II: Use of Non-Ionising Radiation		
Appendix III: Use Medical Devices		

12

Appendix B-2 Information Sheet

55

University College London (UCL) Speech and Language Therapy

Information Sheet for *Parents of Children* in Research Studies

You will be given a copy of this information sheet.

Title of Project: Developmental pre-requisites for use of eye control technology

This study has been approved by the UCL Research Ethics Committee (Project ID Number): **1328/006**

Name	Dr Michael Clarke and Emily Upton
Work Address	Chandler House, University College London, 2 Wakefield Street, London WC1N 1PF
Contact Details	Email: ▮▮▮▮▮▮▮▮ Tel: ▮▮▮▮▮▮

We would like to invite you and your child to take part in a research study. Before you decide, you need to understand why the research is being done and what it would involve for you. Please take time to read the following information carefully. Talk to others about the study if you wish. This information sheet tells you about the purpose of the study and what will happen if you take part.

Purpose of the study

Young children with physical disabilities can find it very difficult to use computers for learning and play because they cannot control a computer mouse. However, new eye control technologies can allow some children to control a computer through eye-movements only. The eye control technology uses cameras and infra-red light built into a computer monitor to follow the user's eye gaze movements. There are no wires or physical connections involved. This technology represents a major breakthrough in the support of people with disabilities and is increasingly being recommended for young children with physical impairments. However, to date, there is very little guidance on how old children need to be before they can learn to use their eyes to control a computer. This project is looking into this issue. Can very young children learn this skill or do children need to be a bit older to be able to take full advantage of eye control technology?

Why has my child been invited to take part?

We are writing to you because your child attends (insert name) nursery/school, which has agreed to support us in this work.

What would participation involve?

If you are willing for your child to take part in the study, we would like to use eye control technology with him/her to carry out some simple games designed specifically for children. Your child will simply be asked to look at the computer screen, and the computer will work out where they are looking.

56

For example, looking at different parts of the screen, such as the blue or yellow button, makes the mouse climb the stairs to get the cheese.
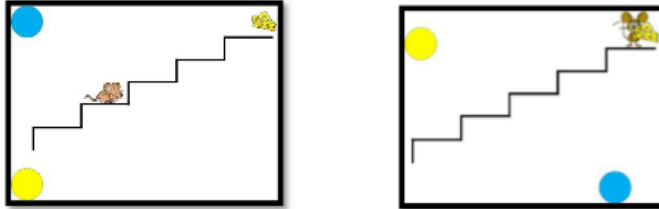
We would also like to carry out some simple assessments of language and learning with your child. These are commonly used activities that simply ask your child to point to pictures in books or to describe a picture. We'd be happy to let you know how they got on with these.

Does my child have to take part?

It is up to you to decide. If, after reading this information sheet, you decide that your child can take part in the study, we ask that you sign and return the enclosed consent form to the nursery in the envelope provided. Please do not hesitate to contact us to ask any questions you may have.

If I agree to take part what will happen if I decide not to carry on?

It is important that you are aware that your participation in this study is strictly voluntary. You are free to withdraw your consent at any time without giving a reason. Withdrawing your consent will not affect your child's care/education.

Will taking part be kept confidential?

Yes. We will follow ethical and legal practice and all information about your child will be handled in confidence. We will not collect data such as your child's name and address. All data will be collected and stored in accordance with the Data Protection Act 1998.

What will happen to the results of the study?

The researchers carrying out the study are students at UCL and they will write-up the findings in a report as part of their studies. We also aim to publicise our findings through journal articles and through presentations at conferences in the UK and abroad. Your child will not be identified explicitly in any report, publication or presentation.

Who is organising and funding the research?

The research is being organised by the Developmental Science Department, University College London. The study forms part of the course of students who are studying to be speech and language therapists at University College London, or who are qualified clinicians undertaking postgraduate study.

57

Who has reviewed the study?

This research study has been looked at and given a favourable opinion by an independent group of people called a Research Ethics Committee to protect your safety, rights, wellbeing and dignity.

What if I have questions about the study?

Please do not hesitate to contact Michael Clarke at University College London (█████████ █████████), if there is anything that is not clear, or if you would like more information.

What if I have a problem with the study?

If you wish to complain, or have any concerns about any aspect of the way you have been approached or treated by members of staff or about any side effects (adverse events) you may have experienced due to your participation in the research, the normal University College London complaints mechanisms are available to you. Please ask members of the research team if you would like more information on this.

What next?

If you are happy for your child to take part after reading about the study, please return the signed consent form in the envelope provided. We will let you know via nursery/school when we hope to visit your child in nursery/school.

Best wishes

Dr Michael Clarke and Emily Upton

Developmental Science Department, UCL

All data will be collected and stored in accordance with the Data Protection Act 1998.

Appendix B-3 Consent Form

58

UCL
UCL SPEECH AND LANGUAGE THERAPY

Informed Consent Form for *Parents of Children* in Research Studies

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Project: Developmental pre-requisites for use of eye control technology

This study has been approved by the UCL Research Ethics Committee (Project ID Number): 1328/006

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you.

If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you to decide whether o join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Participant's Statement

[insert name] _____

- have read the notes written above and the Information Sheet, and understand what the study involves.

- understand that if I decide at any time that I no longer wish my child to take part in this project, I can notify the researchers involved and withdraw my child immediately.

- understand that data collected by the research will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998.

- understand that you will not collect personal information about me or my child such as their name and address

- agree that the research project named above has been explained to me to my satisfaction and I agree that my child can take part in this study.

- I agree that non-personal research data may be used by others for future research. I am assured that the confidentiality of my personal data will be upheld through the removal of identifiers.

Signed: Date:

Appendix C-1 Ethics Application Form

UCL

APPLICATION FORM

SECTION A	APPLICATION DETAILS

A1 **Project Title: Can young children control technology with there eyes rather than their hands?**

Date of Submission: 30 January 2017	Proposed Start Date: 1 March 2017
UCL Ethics Project ID Number: 1328/009	Proposed End Date: 1 December 2017

If this is an application for classroom research as distinct from independent study courses, please provide the following additional details:

Course Title:	Course Number:

A2 **Principal Researcher**
Please note that a student – undergraduate, postgraduate or research postgraduate cannot be the Principal Researcher for Ethics purposes.

Full Name: Michael Clarke	Position Held: Senior Lecturer
Address: Chandler House 2 Wakefield Street London WC1N 1PF	Email: ▮
	Telephone: ▮
	Fax:

Declaration To be Signed by the Principal Researcher

- I have met with and advised the student on the ethical aspects of this project design *(applicable only if the Principal Researcher is not also the Applicant).*

  - I understand that it is a UCL requirement for both students & staff researchers to undergo Disclosure and Barring Service (DBS) Checks when working in controlled or regulated activity with children, young people or vulnerable adults. The required DBS Check Disclosure Number(s) is: Amy Cook 001460859889; Charlotte Whitwood 001497112731

- I have obtained approval from the UCL Data Protection Officer stating that the research project is compliant with the Data Protection Act 1998. My Data Protection Registration Number is: tbc

- I am satisfied that the research complies with current professional, departmental and university guidelines including UCL's Risk Assessment Procedures and insurance arrangements.

- I undertake to complete and submit the 'Continuing Review Approval Form' on an annual basis to the UCL Research Ethics Committee.

- I will ensure that changes in approved research protocols are reported promptly and are not initiated without approval by the UCL Research Ethics Committee, except when necessary to eliminate apparent immediate hazards to the participant.

- I will ensure that all adverse or unforeseen problems arising from the research project are reported in a timely fashion to the UCL Research Ethics Committee.

- I will undertake to provide notification when the study is complete and if it fails to start or is abandoned.

SIGNATURE: ▮▮▮▮▮▮▮▮▮   **DATE:** 30-01-17

A3	**Applicant(s) Details** *(if Applicant is not the Principal Researcher e.g. student details):*

Full Name: Amy Cook

Position Held: Student: MSc Speech and Language Sciences

Address: Chandler House 2 Wakefield Street London WC1N 1PF	Email: ▮▮▮▮▮▮▮
	Telephone:
	Fax:

Full Name: Charlotte Whitwood

Position Held: Student: MSc Speech and Language Sciences

Address: Chandler House 2 Wakefield Street London WC1N 1PF	Email: ▮▮▮▮▮▮▮
	Telephone:
	Fax:

A4	**Sponsor/ Other Organisations Involved and Funding**

a) **Sponsor:** ☒ UCL ☐ Other institution

   If your project is sponsored by an institution other than UCL please provide details:

b) **Other Organisations**: If your study involves another organisation, please provide details. *Evidence that the relevant authority has given permission should be attached or confirmation provided that this will be available upon request.*

c) **Funding:** What are the sources of funding for this study and will the study result in financial payment or payment in kind to the department or College? *If study is funded solely by UCL this should be stated, the section should not be left blank.* The study is funded by UCL

A5	**Signature of Head of Department** [or Chair of the Departmental Ethics Committee]

(This must not be the same signature as the Principal Researcher)

A.   I have discussed this project with the principal researcher who is suitably qualified to carry out this research and I approve it.

I am satisfied that *[please highlight as appropriate]*:

(1)   Data Protection registration:

- has been satisfactorily completed ☐
- has been initiated ☒
- is not required ☐

(2)   a risk assessment:

- has been satisfactorily completed ☐
- has been initiated ☒

(3)   appropriate insurance arrangements are in place and appropriate sponsorship [funding] has been approved and is in place to complete the study.   ☒ Yes   ☐ No

(4)   a Disclosure and Barring Service check(s):

- has been satisfactorily completed ☒
- has been initiated ☐
- is not required ☐

Links to details of UCL's policies on the above can be found at: http://ethics.grad.ucl.ac.uk/procedures.php

2

**If any of the above checks are not required please clarify why below.

B. Having read the 'criteria of minimal risk' as defined on page 3 of our Guidelines at: *http://ethics.grad.ucl.ac.uk/forms/guidelines.pdf* I recommend that this application should be considered by the Chair of the UCL REC.

☐ Yes   ☒ No

PRINT NAME: Merle Mahon

SIGNATURE: ███████████   **DATE:** 26 January 2017

SECTION B	DETAILS OF THE PROJECT

B1 | **Please provide a brief summary of the project in simple prose outlining the intended value of the project, giving necessary scientific background** (*max 500 words*).

In recent years eye-control has been used increasingly to support people with severe physical disabilities to control technology, such as a personal computer or speech generating device. Eye-control technology tracks the position of the eyes and allows the user to control a curser on the screen simply through eye movements. The eye-tracking technology uses cameras and infra-red light built into a computer to monitor the user's eye gaze movements; there are no wires or physical connections involved. This technology represents a major breakthrough in the support of people with disability and is being increasingly recommended for developmentally XX young children with disabilities. However, to date, little guidance is available on the developmental skills that children require in order to make best use of the technology provided. Without this guidance families and schools risk disappointment, technological abandonment, and considerable financial loss if/when they purchase expensive eye control technology. This study aims to establish whether or not young typically developing children can learn to use eye-control technology to carry out a simple cause and effect activity on a computer. The current study builds on an earlier student project (1328/006) that examined the same ability in children aged 18 – 47 months (Mean age = 34.03). In the previous study children with chronological age ≤ 22 months and developmental ages of ≤ 24 months were unable to use eye-gaze control to complete the tasks. It is possible that younger children may be more successful in learning to use eye-control technology with tasks that present more visually salient stimuli. The current project therefore aims to test this hypothesis by redesigning the original cause and effect activity with more visually engaging materials The study will also compare child performance on eye-control technology with performance from a matched group using touch screen technology which provides tactile feedback.

B2 | **Briefly characterise in simple prose the research protocol, type of procedure and/or research methodology (e.g. observational, survey research, experimental). Give details of any samples or measurements to be taken** (*max 500 words*).

Research questions:

1. At what developmental age are children able to maintain sustained attention in order to learn and use eye control technology?

2. At what developmental age are children able to apply knowledge of cause and effect to complete a simple game on an eye gaze technology?

3. What differences are there in speed of learning and accuracy of use in children using eye-control technology versus touch screen technology?

Participants:

This cross-sectional project will work with a cohort of 50 typically developing children aged 9 -36 months.

Measures/procedures:

3

Children will be presented with two learning phases and an experimental phase.

Learning phase: In the first learning phase the child will be shown an 'active' item (e.g. a dancing banana) on a computer screen. When the child looks at the item (child fixes gaze on item for 1 second) it will activate a short children's video as a reward. After 6 trials the will be presented with a 'non-active' item (e.g. dancing gherkin) that does not reward the child when it is looked at.

Experimental phase: In the experimental phase the child will be presented with both the active and non-active items. The dependent variables will be: (i) the number of trials taken to successfully trigger the target button six times in a row (ii) the time taken from the presentation of each scenario for each child to activate the target button (iii) the time taken for each child to activate the target button on 6 consecutively correct trials.

The experimental phase will be repeated 6 times with novel pairs of active and inactive items.

The experiment will also be replicated on a matched group of children using a touch screen computer rather than an eye-control system.

Background measures:

The children's development level will be determined through the use of well-established measures of language (Pre-School Language Scale-5*), and cognition (Mullen Scale of Early Learning**)

Analysis:

An initial investigation of descriptive statistics will be used to characterise performance on both technologies and to compare performance between groups. Scores gained from children of different developmental ages will be compared. Correlational analysis will examine relations between background measures and child performance.

References:

*Zimmerman, I.L., Steiner, V.G., Evatt Pond, R. Preschool Language Scale, Fourth Edition (PLS-5). London: Pearson; 2002.

** Mullen EM. Mullen scales of early learning. Circle Pines, MN: American Guidance Service.; 1984.

Attach any questionnaires, psychological tests, etc. (a standardised questionnaire does not need to be attached, but please provide the name and details of the questionnaire together with a published reference to its prior usage).

B3	**Where will the study take place (please provide name of institution/department)?**
	If the study is to be carried out overseas, what steps have been taken to secure research and ethical permission in the study country? Is the research compliant with Data Protection legislation in the country concerned or is it compliant with the UK Data Protection Act 1998?
	The study will take place in children's nurseries.

B4	**Have collaborating departments whose resources will be needed been informed and agreed to participate?**
	Attach any relevant correspondence.
	n.a.

B5	**How will the results be disseminated, including communication of results with research participants?**
	The results will be used in the dissertations of the research students, and disseminated in academic fora. Parents will receive specific information relating to their child, on request. Nursery staff will be provided with a summary of the outcomes of the study.

4

B6	Please outline any ethical issues that might arise from the proposed study and how they are be addressed. *Please note that all research projects have some ethical considerations so do not leave this section blank.*

Although the study procedures are not invasive we recognise that it is possible that some young children may display distress or anxiety at the presence of researchers or during assessment.

The research students are experienced in working with children (as clinicians and student speech and language therapists) and will assess the response of the child to study procedures.

If a child displays anxiety or distress, we will immediately stop procedures and only proceed after a suitable interval, and/or, following guidance from parents or school/nursery staff. We will withdraw children from the study where they demonstrate on-going distress or anxiety

SECTION C	DETAILS OF PARTICIPANTS

C1 Participants to be studied

C1a. Number of volunteers:	50
Upper age limit:	36 months
Lower age limit:	9 months

C1b. Please justify the age range and sample size:

The project has been designed to be effective in meeting its aims, and achievable within the timeframe available given the reasonable expectations for the research students' commitment to the project.

C2	If you are using data or information held by a third party, please explain how you will obtain this. You should confirm that the information has been obtained in accordance with the UK Data Protection Act 1998.

N.a.

C3	Will the research include children or vulnerable adults such as individuals with a learning disability or cognitive impairment or individuals in a dependent or unequal relationship? ☒ Yes ☐ No

How will you ensure that participants in these groups are competent to give consent to take part in this study? *If you have relevant correspondence, please attach it.*

Consent will be given by parents of the children involved. Given the age of the children under study we do not expect to gain informed assent although as mentioned we will be sensitive to their response to assessment activities, treating behaviours that signal fatigue or anxiety as withdrawal of assent to participate at that time.

C4	Will payment or any other incentive, such as gift service or free services, be made to any research participant? ☐ Yes ☒ No

If yes, please specify the level of payment to be made and/or the source of the funds/gift/free service to be used.

Please justify the payment/other incentive you intend to offer.

5

C5	**Recruitment**

(i) Describe how potential participants will be identified:

Children will be identified via local nurseries

(ii) Describe how potential participants will be approached:

Nursery leaders will be approached about the research. Where they agree to support the work they will send home the information sheet to families

(iii) Describe how participants will be recruited:

Given our opt-out approach, we will wait for a period of 2 weeks after information has been disseminated before beginning testing.

Attach recruitment emails/adverts/webpages. A data protection disclaimer should be included in the text of such literature.

C6	**Will the participants participate on a fully voluntary basis?**	☒ Yes ☐ No

Will UCL students be involved as participants in the research project? ☐ Yes ☒ No

If yes, care must be taken to ensure that they are recruited in such a way that they do not feel any obligation to a teacher or member of staff to participate.

Please state how you will bring to the attention of the participants their right to withdraw from the study without penalty?

C7	**CONSENT**

Please describe the process you will use when seeking and obtaining consent.

All families of children in participating nurseries will receive full information about the project procedures (see information sheets attached), and will have opportunities to discuss the project with research staff and to withdraw their consent. Given our opt-out approach, we will allow a period of 2 weeks for parents to contact the research team to ask questions and/or to opt out before testing begins.

A copy of the participant information sheet and consent form must be attached to this application. For your convenience proformas are provided in C10 below. These should be filled in and modified as necessary.

In cases where it is not proposed to obtain the participants informed consent, please explain why below.

C8	**Will any form of deception be used that raises ethical issues? If so, please explain.**

No

C9	**Will you provide a full debriefing at the end of the data collection phase?**	☐ Yes ☒ No

If 'No', please explain why below.

The results will be used in the dissertations of the research students, and disseminated in academic fora. Parents will receive specific information relating to their child, on request. Nursery staff will be provided with a summary of the outcomes of the study.

6

C10	**Information Sheets And Consent Forms**

A poorly written Information Sheet(s) and Consent Form(s) that lack clarity and simplicity frequently delay ethics approval of research projects. The wording and content of the Information Sheet and Consent Form must be appropriate to the age and educational level of the research participants and clearly state in simple non-technical language what the participant is agreeing to. Use the active voice e.g. "we will book" rather than "bookings will be made". Refer to participants as "you" and yourself as "I" or "we". An appropriate translation of the Forms should be provided where the first language of the participants is not English. If you have different participant groups you should provide Information Sheets and Consent Forms as appropriate (e.g. one for children and one for parents/guardians) using the templates below. Where children are of a reading age, a written Information Sheet should be provided. When participants cannot read or the use of forms would be inappropriate, a description of the verbal information to be provided should be given. Please ensure that you trial the forms on an age-appropriate person before you submit your application.

(SD)

SECTION D	DETAILS OF RISKS AND BENEFITS TO THE RESEARCHER AND THE RESEARCHED

D1	**Have UCL's Risk Assessment Procedures been followed?** ☒ Yes ☐ No If **No**, please explain.

D2	**Does UCL's insurer need to be notified about your project before insurance cover can be provided?** ☐ Yes ☒ No

The insurance for all UCL studies is provided by a commercial insurer. For the majority of studies, the cover is automatic. However, for a minority of studies, in certain categories, the insurer requires prior notification of the project before cover can be provided.

If **Yes**, please provide confirmation that the appropriate insurance cover has been agreed. *Please attach your UCL insurance registration form and any related correspondence.*

D3	**Please state briefly any precautions being taken to protect the health and safety of researchers and others associated with the project (as distinct from the research participants).**

The data collection will take place in schools and nurseries. Travel for data collection will be undertaken at normal travel times. The students will be working in nursery settings, and typically children will be accompanied by a member of staff. Studetns will ensire that they are informed about the health and saftey polies of nurseries visited. The research students have considerable experience of working in educational and clinical environments as part of their programmes of study (masters students are undergoing training to be speech and language therapists). All students will be aware of UCL's Speech and Language Therapy Policy for working with (vulnerable) children.

7

D4   Will these participants participate in any activities that may be potentially stressful or harmful in connection with this research?   ☐ Yes   ☒ No

If **Yes**, please describe the nature of the risk or stress and how you will minimise and monitor it.

D5   Will group or individual interviews/questionnaires raise any topics or issues that might be sensitive, embarrassing or upsetting for participants?

If **Yes**, please explain how you will deal with this.

n.a.

D6   Please describe any expected benefits to the participant.

There are no direct benefits for parents of typically developing children taking part in the project, but in the long term this work has strong potential to influence clinical practice, and will inform the field of assistive technology research more generally.

D7   Specify whether the following procedures are involved:

Any invasive procedure(s)   ☐ Yes   ☒ No

Physical contact   ☐ Yes   ☒ No

Any procedure(s) that may cause mental distress   ☐ Yes   ☐ No

Please state briefly any precautions being taken to protect the health and safety of the research participants.

Please note that for some children, working with unfamiliar adults could cause raised anxiety or distress. As noted above, we will constantly monitor the impact of activities on the child and take all necessary action to alleviate any distress displayed.

8

D8

Does the research involve the use of drugs? ☐ Yes ☒ No

If **Yes**, please name the drug/product and its intended use in the research and then complete Appendix I

Does the project involve the use of genetically modified materials? ☐ Yes ☒ No

If **Yes**, has approval from the Genetic Modification Safety Committee been obtained for work? ☐ Yes ☐ No

If **Yes**, please quote the Genetic Modification Reference Number:

D9

Will any non-ionising radiation be used on the research participant(s)?

☐ Yes ☒ No

If **Yes**, please complete Appendix II.

D10

Are you using a medical device in the UK that is CE-marked and is being used within its product indication?

☐ Yes ☒ No

If **Yes**, please complete Appendix III.

9

CHECKLIST

Please submit ether 12 copies (1 original + 11 double sided photocopies) of your completed application form for full committee review or 3 copies (1 original + 2 double sided copies) for chair's action, together with the appropriate supporting documentation from the list below to the UCL Research Ethics Committee Administrator. You should also submit your application form electronically to the Administrator at: ethics@ucl.ac.uk

Documents to be Attached to Application Form (if applicable)	Ticked if attached	Tick if not relevant
Section B: Details of the Project		
• Questionnaire(s) / Psychological Tests	☐	☒
• Relevant correspondence relating to involvement of collaborating department/s and agreed participation in the research.	☐	☒
Section C: Details of Participants		
• Parental/guardian consent form for research involving participants under 18	☒	☐
• Participant/s information sheet	☒	☐
• Participant/s consent form/s	☐	☐
• Advertisement	☐	☐
Section D: Details of Risks and Benefits to the Researcher and the Researched		
• Insurance registration form and related correspondence	☐	☒
Appendix I: Research Involving the Use of Drugs		
• Relevant correspondence relating to agreed arrangements for dispensing with the pharmacy	☐	☒
• Written confirmation from the manufacturer that the drug/substance has has been manufactured to GMP	☐	☒
• Proposed volunteer contract	☐	☒
• Full declaration of financial or direct interest	☐	☒
• Copies of certificates: CTA etc…	☐	☒
Appendix II: Use of Non-Ionising Radiation		
Appendix III: Use Medical Devices		

Please note that correspondence regarding the application will normally be sent to the Principal Researcher and copied to other named individuals.

10

Appendix C-2 Information Sheet

UCL

Information Sheet for Parents/Carers
23rd January 2017

Project Title: Can young children control technology with their eyes rather than their hands?

Student Researchers: Amy Cook and Charlotte Whitwood
Principal Supervisor: Dr Michael Clarke

We would like to invite you and your child to take part in a research study. Before you decide, you need to understand why the research is being done and what it would involve for you. Please take time to read the following information carefully. Talk to others about the study if you wish. This information sheet tells you about the purpose of the study and what will happen if you take part.

This study has been approved by the UCL Research Ethics Committee (Project ID Number 1328/009)

What is our study about?
Young children with physical disabilities can find it very difficult to use computers for learning and play because they cannot control a computer mouse. However, new eye control technologies can allow some children to control a computer through eye-movements only. The eye control technology uses cameras and infra-red light built into a computer monitor to follow the user's eye gaze movements. There are no wires or physical connections involved. This technology represents a major breakthrough in the support of people with disabilities and is increasingly being recommended for young children with physical impairments. However, to date, there is very little guidance on how old children need to be before they can learn to use their eyes to control a computer. This project is looking into this issue. Can very young children who do not have disabilities learn this skill or do children need to be a bit older to be able to take full advantage of eye control technology?

Why has my child been invited to take part?
We are writing to you because your child attends (insert name) nursery/school, which has agreed to support us in this work.

What would participation involve?

If you are willing for your child to take part in the study, we would like to carry out come simple play-based computer activities with them. For example, your child would be asked to find fun items on the computer screen (such as a dancing banana). They will be asked to do this with their hands by touching the screen or just by looking (the computer will work out where they are looking and treat their looking just like a finger press).

We would also like to carry out some simple assessments of language and learning with your child. These are commonly used activities that simply ask your child to point to pictures in books or to describe a pictures. We'd be happy to let you know how your child got on with these.

Does my child have to take part?
If you would prefer your child **NOT TO** take part in the study, please sign the OPT-OUT consent form attached to this document and return it to your child's nursery, and your child will NOT be involved in the research. If you are happy for your child to take part you do not need to do anything, there is no form to sign.

If I agree to take part what will happen if I decide not to carry on?
It is important that you are aware that your participation in this study is strictly voluntary. You are free to withdraw your consent at any time without giving a reason. Withdrawing your consent will not affect your child's care/education.

Will taking part be kept confidential?
Yes. We will follow ethical and legal practice and all information about your child will be handled in confidence. We will not collect data such as your child's name and address. All data will be collected and stored in accordance with the Data Protection Act 1998.

What will happen to the results of the study?
The researchers carrying out the study are students at UCL training to be speech and language therapists. They will write-up the findings in a report as part of their studies. We also aim to publicise our findings through journal articles and through presentations at conferences in the UK and abroad. Your child will not be identified explicitly in any report, publication or presentation.

Who is organising and funding the research?
The research is being organised by the Department of Language and Cognition, University College London. The study forms part of the course of students who are studying to be speech and language therapists at University College London.

Who has reviewed the study?
This research study has been looked at and given a favourable opinion by an independent group of people called a Research Ethics Committee to protect your safety, rights, wellbeing and dignity.

What if I have questions about the study?

Please do not hesitate to contact Michael Clarke at University College London (█████ ██████████████████████, if there is anything that is not clear, or if you would like more information.

What if I have a problem with the study?

If you wish to complain, or have any concerns about any aspect of the way you have been approached or treated by members of staff or about any side effects (adverse events) you may have experienced due to your participation in the research, the normal University College London complaints mechanisms are available to you. Please ask members of the research team if you would like more information on this.

What next?

If you are happy for your child to take part after reading about the study you do not need to do anything. If you would prefer your child not to take part in the research please sign and return the opt-out form provided.

█████████████

Best wishes
Dr Michael Clarke
Language and Cognition Department, UCL

All data will be collected and stored in accordance with the Data Protection Act 1998.

Dr Michael Clarke
Department of Language and Cognition
Chandler House
2 Wakefield Street
London
WC1N 1PF
████████████████

Amy Cook & Charlotte Whitwood
Department of Language and Cognition
Chandler House
2 Wakefield Street
London
WC1N 1PF
███████████████████

Appendix C-3 Consent Form

Informed Consent Form for Parents/Carers

Project Title: Can young children control technology with their eyes rather than their hands?

This study has been approved by the UCL Research Ethics Committee (Project ID Number 1328/009)

Thank you for your interest in allowing your child to take part in this research. If you are happy for your child to take part, there is no need to complete the form.

Please complete this form if you **DO NOT** wish your child to take part in the study.

Child's Name………………………………………..…………………………………

I DO **NOT** WISH MY CHILD to be involved in the study:

Parent/Carer's Name……………………………………..

Parent/Carer Signature ……………………………………

Date…………………………………………………………….

Researcher Name………………………………………….

Researcher Signature……………………………………

Date…………………………………………………………..

Appendix C-4 Score Sheet

Child ID:		Gender:	☐ Male ☐ Female	Notes:
DOB:		Glasses:	☐ Yes ☐ No	

TRIAL 1

Experiment:	☐ Healthy ☐ Unhealthy			Notes:
Passed Active Button?	☐ Yes ☐ No	Passed Null Button?	☐ Yes ☐ No	
1		10		
2		11		
3		12		
4		13		
5		14		
6		15		
7		16		
8		17		
9		18		

TRIAL 2

Experiment:	☐ Healthy ☐ Unhealthy			Notes:
Passed Active Button?	☐ Yes ☐ No	Passed Null Button?	☐ Yes ☐ No	
1		10		
2		11		
3		12		
4		13		
5		14		
6		15		
7		16		
8		17		
9		18		

TRIAL 3

1		10		
2		11		
3		12		
4		13		
5		14		
6		15		
7		16		
8		17		
9		18		

Appendix D-1 Approved Ethics Amendment

Amendment Approval Request Form

1	Project ID Number: 1328/009	Name and Address of Principal Investigator: Dr Michael Clarke Senior Lecturer Chandler House 2 Walkefield Street London WC1N 1PF
2	**Project Title:** Can young children learn or be taught to use eye-gaze access technology instead of a touchscreen to complete sequencing tasks?	
3	**Type of Amendment/s (tick as appropriate)** Research procedure/protocol (including research instruments) ☒ Participant group ☐ Sponsorship/collaborators ☐ Extension to approval needed (extensions are given for one year) ☒ *to 23/2/2019* Information Sheet/s ☒ Consent form/s ☒ Other recruitment documents ☐ Principal researcher/medical supervisor* ☐ Other ☐ *Additions to the research team other than the principal researcher, student supervisor and medical supervisor do not need to be submitted as amendments but a complete list should be available upon request *	
4	**Justification** (give the reasons why the amendment/s are needed) This amendment outlines a minor change to the methodology of an existing study and proposes an extension of this study for a further year to allow researchers to gather further comparative data. This amendment is required to build upon the work carried out in the previous phase of the study and constitutes an extension to the existing protocol, together with the recruitment of a new group of participants matching the original study's criteria.	
5	**Details of Amendments** (provide full details of each amendment requested, state where the changes have been made and attach all amended and new documentation) This amendment proposes that the original task (see original ethics application, attached) be redesigned to slightly. In the previous task children used an eye-control device to pay a cause and effect game. In that task children were encouraged to explore the game independently. In this new version we will compare how children engage with a cause and effect task on both eye-control technology and a touch screen tabled computer. We will also introduce some carefully designed prompts support children to learn the task. These prompts are verbal and direct the child to how to run the activity (e.g. "oh look then you press that button the person waves and smiles, and when you press that button nothing happens").. Whilst this will extend the time that children are required to participate in the tasks, the redesign of the experiment means that the task can better be broken up to provide breaks. The experimental environment and conditions will remain unchanged. The information sheet and consent forms have both been updated to reflect these changes and are attached.	
6	**Ethical Considerations** (insert details of any ethical issues raised by the proposed amendment/s) The researchers do not anticipate that this amendment raises any ethical considerations in addition to those already outlined in the original proposal.	
7	**Other Information** (provide any other information which you believe should be taken into account during ethical review of the proposed changes)	

The research will be carried out by two different researchers from those listed on the original application. Tom Griffiths, PhD student, and Susannah Davis, Masters student, both of whom will continue to be supervised by the Principal Investigator and have full DBS clearance in place.

Declaration (to be signed by the Principal Researcher)

- I confirm that the information in this form is accurate to the best of my knowledge and I take full responsibility for it.
- I consider that it would be reasonable for the proposed amendments to be implemented.
- For student projects, I confirm that my supervisor has approved my proposed modifications.

Signature:

Date:

FOR OFFICE USE ONLY:

Amendments to the proposed protocol have been ...*approved*... by the Research Ethics Committee.

Signature of the REC Chair: ███████ ███████

Date: 09/02/2018

Information Sheet for Parents/Carers
20th January 2018

Project Title: Can young children learn or be taught to use eye-gaze access technology instead of a touchscreen to complete sequencing tasks?

Student Researchers: Tom Griffiths and Susannah Davis
Principal Supervisor: Dr Michael Clarke

We would like to invite you and your child to take part in a research study. Before you decide, you need to understand why the research is being done and what it would involve for you and for your child. Please take time to read the following information carefully. Talk to others about the study if you wish. This information sheet tells you about the purpose of the study and what will happen if you take part.

This study has been approved by the UCL Research Ethics Committee (Project ID Number 1328/009)

What is our study about?
Young children with physical disabilities can find it very difficult to use computers for learning and play because they cannot control a computer mouse and keyboard. However, eye-gaze technologies can allow some children to control a computer through eye-movements only. The eye-gaze technology uses cameras and infra-red light to follow the user's eye movements. There are no wires or physical connections involved. This technology represents a major breakthrough in the support of people with disabilities and is increasingly being recommended for young children with physical impairments. However, to date, there is very little guidance on how old children need to be before they can learn to use their eyes to control a computer. This project is looking into this issue: can very young children who do not have disabilities learn this skill or do children need to be a bit older to be able to take full advantage of eye-gaze technology? Additionally, we will be exploring if the skills needed are "teachable" in the same way as children can be taught to use a touchscreen computer.

Why has my child been invited to take part?

We are writing to you because your child attends (insert name) nursery/school, which has agreed to support us in this work.

What would participation involve?
If you are willing for your child to take part in the study, we would like to carry out come simple play-based computer activities with them. For example, your child would be asked to find fun items and videos on a computer screen. They will be asked to do this with their hands by touching the screen and just by looking (the computer will work out where they are looking and treat their looking just like a finger press).

We would also like to carry out some simple assessments of language and learning with your child. These are commonly used activities that simply ask your child to point to pictures in books or to describe a pictures. We'd be happy to let you know how your child got on with these.

Does my child have to take part?
If you would prefer your child **NOT TO** take part in the study, please sign the **OPT-OUT** consent form attached to this document and return it to your child's nursery, and your child will **NOT** be involved in the research. If you are happy for your child to take part you do not need to do anything, there is no form to sign.

If I agree to take part what will happen if I decide not to carry on?
It is important that you are aware that your participation in this study is strictly voluntary. You are free to withdraw your consent at any time without giving a reason. Withdrawing your consent will not affect your child's care/education.

Will taking part be kept confidential?
Yes. We will follow ethical and legal practice and all information about your child will be handled in confidence. We will not collect data such as your child's name and address. All data will be collected and stored in accordance with the Data Protection Act 1998. The process of recording and storing data has been approved by the ethics committee at UCL as conforming with all requirements for safety and data protection.

What will happen to the results of the study?
The researchers carrying out the study are students at UCL. They will write-up the findings in a report as part of their studies. We also aim to publicise our findings through journal articles and through presentations at conferences in the UK and abroad. Your child will not be identified explicitly in any report, publication or presentation.

Who is organising and funding the research?
The research is being organised by the Department of Language and Cognition, University College London. The students carrying out the work are involved in Masters and Doctoral level study within this department.

Who has reviewed the study?

This research study has been looked at and given a favourable opinion by an independent group of people called a Research Ethics Committee to protect your safety, rights, wellbeing and dignity.

What if I have questions about the study?
Please do not hesitate to contact Michael Clarke at University College London █████
████████████████████), if there is anything that is not clear, or if you would like more information.

What if I have a problem with the study?
If you wish to complain, or have any concerns about any aspect of the way you have been approached or treated by members of staff or about any side effects (adverse events) you may have experienced due to your participation in the research, the normal University College London complaints mechanisms are available to you. Please ask members of the research team if you would like more information on this.

What next?
If you are happy for your child to take part after reading about the study you do not need to do anything. **If you would prefer your child not to take part in the research please sign and return the opt-out form provided.**

███████████

Best wishes
Dr Michael Clarke
Language and Cognition Department, UCL

All data will be collected and stored in accordance with the Data Protection Act 1998.

Dr Michael Clarke
Department of Language and Cognition
Chandler House
2 Wakefield Street
London
WC1N 1PF
████████████████

Tom Griffiths and Susannah Davis
Department of Language and Cognition
Chandler House
2 Wakefield Street
London
WC1N 1PF
████████████████

Informed Consent Form for Parents/Carers

Project Title: Can young children control technology with their eyes rather than their hands?

This study has been approved by the UCL Research Ethics Committee (Project ID Number 1328/009)

Thank you for your interest in allowing your child to take part in this research. If you are happy for your child to take part, there is no need to complete the form.

Please complete this form if you **DO NOT** wish your child to take part in the study.

Child's Name……………………………………………..…………………………………

I DO **NOT** WISH MY CHILD to be involved in the study:

Parent/Carer's Name……………………………………..

Parent/Carer Signature ……………………………………

Date…………………………………………………….

Researcher Name………………………………………….

Researcher Signature……………………………………

Date……………………………………………………..

Appendix D-4 Score Sheet

Participant number: Age (months):   Passed cause and effect task? ☐

Condition: Eye-gaze – Touchpad ☐   Touchpad – Eye-gaze ☐

Current modality: Touchpad ☐   Eye-gaze ☐   Eye-gaze calibrated? ☐

Testing Phase 1

Trial	Active Icon selected?	Notes (fail type N=Null, S=rest of screen)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		

Testing Phase 2

Trial	Active icon selected?	Notes (fail type N=Null, S=rest of screen)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		

Feedback given in Intervention:

Intervention trials successful? 1☐   2☐   3☐   4☐   5☐   6☐

Appendix D-5 Python Code to Randomise Position of Stimulus

```python
import me4

def setVideoPos():
    global thisCell
    x=thisCell.GetPosX()
    y=thisCell.GetPosY()
    iPage=me4.Doc().PageByName("videofull")
    tCells=iPage.Cells()
    tDstCell=iPage.Cell(x,y)
    for c in tCells:
        acts=c.Actions()
    #we found the video cell, now move it to the correct
    position
        if len(acts) > 0:
            me4.Doc().SwapCells(tDstCell,c)
            break
    return
```

Appendix E-1 Ethics Amendment Request & Approval Email

UCL RESEARCH ETHICS

Amending an Approved Application

Should you wish to make an amendment to an approved study, you will need to submit an 'amendment request' for the consideration of the Chair of the UCL Research Ethics Committee. Applications can only be amended **after** ethical approval has been granted.

You will need to apply for an amendment approval if you wish to:

1. Add a new participant group;
2. Add a new research method;
3. Ask for additional data from your existing participants;
4. Remove a group of participants or a research method from the project, and have not yet commenced that part of the project;
5. Apply for an extension to your current ethical approval.

If you need to apply for an amendment approval, please complete the Amendment Approval Request Form on the next page.

When completing the form, please ensure you do the following:

- Clearly explain what the amendment you wish to make is, and the justification for making the change.
- Insert details of any ethical issues raised by the proposed amendments.
- Include all relevant information regarding the change so that the Chair can make an informed decision, and submit a copy of the sections of your application that have changed with all changes highlighted/underlined for clarity.
- You do not need to submit your original application in full again. However, if the changes you wish to make alters several sections of your application form, you are advised to submit this.

Please email a signed electronic copy to the REC Administrator: ethics@ucl.ac.uk

Amendment requests are generally considered within 5-7 days of submission.

Amendment Approval Request Form

1	**Project ID Number:** 1328/009	**Name and Address of Principal Investigator:** Dr Michael Clarke Senior Lecturer Chandler House 2 Walkefield Street London WC1N 1PF
2	**Project Title:** Can young children with cerebral palsy learn or be taught to use eye-gaze access technology instead of a touchscreen to complete sequencing tasks?	
3	**Type of Amendment/s (tick as appropriate)** Research procedure/protocol (including research instruments) ☒ Participant group ☒ Sponsorship/collaborators ☐ Extension to approval needed (extensions are given for one year) ☒ Information Sheet/s ☒ Consent form/s ☐ Other recruitment documents ☐ Principal researcher/medical supervisor* ☐ Other ☐ *Additions to the research team other than the principal researcher, student supervisor and medical supervisor do not need to be submitted as amendments but a complete list should be available upon request *	
4	**Justification** (give the reasons why the amendment/s are needed) This amendment is requested for an additional patient group to be added to the study and proposes an extension of this study for a further year to allow researchers to gather comparative data on newly recruited group of children using both touchscreen and eye-gaze technology. This amendment is required to build upon the work carried out in the previous phase of the study and constitutes an extension to the existing protocol, together with the recruitment of a new group of participants – children with cerebral palsy aged 4 -12 years. The addition of two background measures (of language understanding and functional vision skills) is also part of this requested amendment, although both have been included in previous versions of the experimental protocol. These measures will provide objective measurements of the participant's understanding of language, which previous	

	versions of the study have shown to be an effective indicator of general cognition, and of functional vision skills which are important to the use of eye-gaze technology.
5	**Details of Amendments** (provide full details of each amendment requested, state where the changes have been made and attach all amended and new documentation) This amendment proposes that the original task (see original ethics application and previous amendment, attached) be conducted with a new participant group, as described above. It is proposed that the same task will be carried out on a touchscreen device to provide comparison data for the group's performance with eye-gaze technology. In addition, the *Peabody Picture Vocabulary Test* will be used to provide a measure of children's receptive language level and the *Rapid Assessment of Functional Vision Skills* (https://www.ucl.ac.uk/gaze/funvis). A questionnaire will be given to parents asking them to provide information on how their child uses their vision in everyday life. Whilst these will extend the time that children are required to participate in the tasks, the redesign of the experiment means that sessions can better be broken up to provide breaks, including the possibility of separating the background and experimental measures and conducting these on different days. The experimental environment and conditions will remain unchanged. The information sheet and consent forms have both been updated to reflect these changes and are attached.
6	**Ethical Considerations** (insert details of any ethical issues raised by the proposed amendment/s) The researchers do not anticipate that this amendment raises any ethical considerations in addition to those already outlined in the original proposal.
7	**Other Information** (provide any other information which you believe should be taken into account during ethical review of the proposed changes) The research will be carried out by a different researcher to those listed on the original application. Tom Griffiths, PhD student, will continue to be supervised by the Principal Investigator and has full DBS clearance in place.

Declaration (to be signed by the Principal Researcher)

- I confirm that the information in this form is accurate to the best of my knowledge and I take full responsibility for it.
- I consider that it would be reasonable for the proposed amendments to be implemented.
- For student projects, I confirm that my supervisor has approved my proposed modifications.

Signature:

Date:

- -

FOR OFFICE USE ONLY:

Amendments to the proposed protocol have been ………………… by the Research Ethics Committee.

Signature of the REC Chair:

Date:

Date: 7 Jan 2019, 15:58 +0000
To: VPRO.Ethics <ethics@ucl.ac.uk>

Dear Michael,

The REC Chair has approved your amendment request and the ethical approval of your study has been extended to **23/02/2020**.

Please provide us with a signed copy of your amendment request form for our records.

IMPORTANT: For projects collecting personal data only
Change to legal basis for the processing of data: If you are processing (i.e. collecting, storing, using, disclosing or destroying) identifiable personal information about living individuals as part of your research then you should ensure that you comply with the requirements of the GDPR and the Common Law Duty of Confidentiality. An appropriate legal basis for the processing of your data must be identified, and you must be explicit about this and document it as part of your ethics application, and in the information you provide to your research participants. UCL's view is that, for the vast majority of research undertaken at UCL, the appropriate legal basis will be 'a task in the Public interest': the processing is necessary for UCL to perform a task in the public interest - rather than 'consent'.

However, even though the legal basis for the processing of a person's data is most likely to be 'a task in the public interest' rather than 'consent', from an ethical perspective,

obtaining a person's informed consent for their involvement in the research is still likely to be required in order to abide by the fairness and transparency elements of principle GDPR Article 5(1)(a) or to meet confidentiality obligations.

We have recently changed the data privacy section of our template participant information sheet (PIS) to reflect this change to the legal basis for data processing - see attached. You will need to update your PIS accordingly.

With best wishes for the research,

Ed

Appendix E-2 Information Sheet

Participant Information Sheet For Children with Cerebral Palsy

UCL Research Ethics Committee Approval ID Number: 1328-009

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title of Study: Can young children with cerebral palsy learn or be taught to use eye-gaze access technology to complete sequencing tasks?

Department: Division of Psychology & Language Sciences

Name and Contact Details of the Researcher(s): Tom Griffiths, PhD Researcher

████████████████████

Name and Contact Details of the Principal Researcher: Dr Michael Clarke, Senior Lecturer

████████████████

1. **Invitation Paragraph**

   We would like to invite you and your child to take part in a research study. Before you decide, you need to understand why the research is being done and what it would involve for you and for your child. Please take time to read the following information carefully. Talk to others about the study if you wish. This information sheet tells you about the purpose of the study and what will happen if you take part.

2. **What is the project's purpose?**

   Young children with physical disabilities can find it very difficult to use computers for communication, learning and play because they cannot control a computer mouse and keyboard. However, eye-gaze technologies can allow some children to control a computer through eye-movements only. The eye-gaze technology uses cameras and infra-red light to follow the user's eye movements. This technology represents a major breakthrough in the support of people with disabilities and is increasingly being recommended for young children with physical impairments. However, to date, there is very little guidance on how old children need to be before they can learn to use their eyes to control a computer and it is unclear how children's "functional vision" (the use of vision for completing tasks such as signalling messages and making choices) might affect their use of this technology. This project is looking into the following questions:

   - What impact does the development of functional vision have on performance with an eye-gaze system?
   - For children with cerebral palsy who present with impaired functional vision skills, will "teaching" use of eye-gaze technology have any impact on performance?

3. **Why has my child been chosen?**

Your child has been chosen to take part because they attend [SCHOOL], has a diagnosis of cerebral palsy and are aged between 4 and 12 years old.

4. **Do I have to take part?**
    Your child **DOES NOT** have to be involved in this research and they will not be included without your consent, which is given by reading and signing the attached consent form. If you do not sign the form, your child will **NOT** be involved in the research.

5. **What will happen to my child if I agree to their taking part?**
    If you are willing for your child to take part in the study, we would like to carry out some simple play-based computer activities with them, conduct a simple assessment of language understanding and carry out a brief functional vision screening assessment to see how they use their vision.

    We would like to carry out some simple assessments of language and learning with your child. These are commonly used activities that simply ask your child to point to pictures in books or to indicate their choice using their *yes* and *no* responses. We will also conduct a brief assessment of how your child uses their vision, which will involve looking at items as they are held up and moved around, in order for us to observe how they move their eyes. We'd be happy to let you know how your child got on with either or both of these.

    We would also like to ask you to complete a short questionnaire about how your child uses their vision in day-to-day life, which will provide us with background information for the other tasks in the study.

    For the main part of the experiment, your child will be asked to find fun items and videos on a computer screen. They will be asked to do this just by looking (the computer will work out where they are looking and treat their looking just like a finger press).

    If you feel that fatigue could be an issue for your child, we could split the experiments over two different days, carrying out the language and vision tasks on one and the computer-based tasks on another.

6. **Will I be recorded and how will the recorded media be used?**
    Video recording will be used during the sessions to assist the researchers in analysing the outcome of the experiments. The video recordings of your child's activities made during this research will be used only for analysis and for illustration in conference presentations and lectures. No other use will be made of them without your written permission, and no one outside the project will be allowed access to the original recordings.

7. **What are the possible disadvantages and risks of taking part?**
    No risks or disadvantages to your child's taking part in the study have been identified. In the event that your child displays any signs of discomfort or distress at any point during the study, we will ensure that the study is interrupted and that a suitable break is given. If your child does not wish to continue with the study, we will stop the study.

8. **What are the possible benefits of taking part?**
    Whilst there are no immediate benefits for those people participating in the project, it is hoped that this work will help provide insight into how young children with cerebral palsy

use eye-gaze technology at an early stage and how clinicians might best help new eye-gaze users to make the best progress.

9. **What if something goes wrong?**

If you feel that something has gone wrong, if you wish to complain, or have any concerns about any aspect of the way you have been approached or treated by members of staff or about any side effects (adverse events) you may have experienced due to your participation in the research, the normal University College London complaints mechanisms are available to you. Please ask members of the research team if you would like more information on this. Please do not hesitate to contact Michael Clarke at University College London (█████████████████████████, if there is anything that is not clear, or if you would like more information.

10. **Will my taking part in this project be kept confidential?**

Yes. We will follow ethical and legal practice and all information about your child will be handled in confidence. All the information that we collect about you and your child during the course of the research will be kept strictly confidential. You will not be able to be identified in any ensuing reports or publications.

11. **Limits to confidentiality**

Please note that assurances on confidentiality will be strictly adhered to unless evidence of wrongdoing or potential harm is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

12. **What will happen to the results of the research project?**

The researcher carrying out the study is a student at UCL. The findings will be written up as part of a doctoral thesis. We also aim to publicise our findings through journal articles and through presentations at conferences in the UK and abroad. Your child will not be identifiable in any report, publication or presentation.

13. **Data Protection Privacy Notice**

Notice:

The data controller for this project will be University College London (UCL). The UCL Data Protection Office provides oversight of UCL activities involving the processing of personal data, and can be contacted at data-protection@ucl.ac.uk. UCL's Data Protection Officer is Lee Shailer and he can also be contacted at data-protection@ucl.ac.uk*.*

Your personal data will be processed for the purposes outlined in this notice. The legal basis that would be used to process your personal data will be the provision of your consent. You can provide your consent for the use of your personal data in this project by completing the consent form that has been provided to you.

Your personal data will be processed so long as it is required for the research project, to a maximum of two years. If we are able to anonymise or pseudonymise the personal data you provide we will undertake this, and will endeavour to minimise the processing of personal data wherever possible.

If you are concerned about how your personal data is being processed, please contact UCL in the first instance at data-protection@ucl.ac.uk. If you remain unsatisfied, you may wish to contact the Information Commissioner's Office (ICO). Contact details, and details of data subject rights, are available on the ICO website at: https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/individuals-rights/

14. **Who is organising and funding the research?**

The research is being organised by the Department of Language and Cognition, University College London. The researcher carrying out the work is involved in Doctoral level study within this department.

16. **Contact for further information**

Please do not hesitate to contact Michael Clarke at University College London ████████ ███████████████), if there is anything that is not clear, or if you would like more information.

Thank you for reading this information sheet and for considering to take part in this research study. You will be given a copy of the information sheet and, if appropriate, a signed consent form to keep.

Appendix E-3 Consent Form

CONSENT FORM FOR CHILDREN WITH CEREBRAL PALSY IN RESEARCH STUDIES

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study: Can young children with cerebral palsy learn or be taught to use eye-gaze access technology instead of a touchscreen to complete sequencing tasks?

Department: Division of Psychology & Language Sciences

Name and Contact Details of the Researcher(s): Tom Griffiths, PhD Researcher ██████████████████

Name and Contact Details of the Principal Researcher: Dr Michael Clarke, Senior Lecturer ██████████████

Name and Contact Details of the UCL Data Protection Officer: Lee Shailer, Data Protection and FOI Officer   data-protection@ucl.ac.uk

This study has been approved by the UCL Research Ethics Committee: Project ID number: 1328-009

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

I confirm that I understand that by ticking/initialling each box below I am consenting to this element of the study. I understand that it will be assumed that unticked/initialled boxes means that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element that I may be deemed ineligible for the study.

		Tick Box
1.	I confirm that I have read and understood the Information Sheet for the above study. I have had an opportunity to consider the information and what will be expected of me and my child. My child and I have also had the opportunity to ask questions which have been answered to my satisfaction and I would like my child to take part in:	

	- Assessment of language understanding - Assessment of functional vision skills - Touchscreen games - Eye-gaze games I am happy to participate in the parent questionnaire as it is described in the information sheet.	
2.	I understand that I will be able to withdraw my data or my child's data up to 4 weeks after the date on which the study takes place.	
3.	I consent to the processing of mine and my child's personal information (including name, date of birth, details of disability) for the purposes explained to me. I understand that such information will be handled in accordance with all applicable data protection legislation.	
4.	I understand that all personal information will remain confidential and that all efforts will be made to ensure my child and I cannot be identified. I understand that data gathered in this study will be stored anonymously and securely. It will not be possible to identify my child or I in any publications.	
5.	I understand that my information and my child's information may be subject to review by responsible individuals from the University for monitoring and audit purposes.	
6.	I understand that my participation and my child's participation is voluntary and that I am free to withdraw at any time without giving a reason, without my legal rights being affected. I understand that if I decide to withdraw, or to withdraw my child, any personal data provided up to that point will be deleted unless I agree otherwise.	
7.	I understand the potential risks of participating and the support that will be available to me and my child should we become distressed during the course of the research.	
8.	I understand the benefits of participating.	
9.	I understand that the data will not be made available to any commercial organisations but is solely the responsibility of the researcher(s) undertaking this study.	
10.	I understand that my child and I will not benefit financially from this study or from any possible outcome it may result in in the future.	

11.	I agree that anonymised research data may be used by others for future research.	
12.	I consent to my study being audio/video recorded and understand that the recordings will be: - Stored anonymously, using password-protected software and will be used for training, quality control, audit and specific research purposes. To note: If you do not want your participation recorded you can still take part in the study.	
13.	I hereby confirm that I understand the inclusion criteria as detailed in the Information Sheet and explained to me by the researcher.	
14.	I hereby confirm that: (a) I understand the exclusion criteria as detailed in the Information Sheet and explained to me by the researcher; and (b) My child does not fall under the exclusion criteria.	
15.	I am aware of who I should contact if I wish to lodge a complaint.	
16.	I voluntarily agree to take part in this study.	
17.	I would be happy for the data I provide to be archived at University College London (UCL) for two years after completion of the project. I understand that other authenticated researchers will have access to my anonymised data.	

If you would like your contact details to be retained so that you can be contacted in the future by UCL researchers who would like to invite you to participate in follow up studies to this project, or in future studies of a similar nature, please tick the appropriate box below.

Yes, I would be happy to be contacted in this way	
No, I would not like to be contacted	

_____   _____   _____
Name of participant   Date   Signature

_____   _____   _____
Name of witness   Date   Signature
(If applicable)

_____   _____   _____
Researcher   Date   Signature

Appendix F-1 Ethics Approval Confirmation Letter

NHS
Health Research Authority

Skipton House, Ground Floor,
HRA/NRES
80 London Road
SE1 6LH

Dr Michael Clarke
Chandler House
2 Wakefield Street
London
WC1N 1PF

Dear Dr Clarke

Study title: Functional Gaze control in young children with cerebral palsy

REC Reference: 12/LO/0605

The Research Ethics Committee reviewed the above application on 25th April 2012. I am happy to confirm that the study has received full ethical approval.

Yours sincerely

Kate Donaldson
Assistant Co-ordinator

NRESCommittee.London-Central@nhs.net

Appendix F-2 Invitation Letter

UCL
DEVELOPMENTAL SCIENCE DEPARTMENT

Date xx xx 2012

Dear _____

Re: Early Social Communication Skills of Children with Cerebral Palsy

I am writing to invite you and your child to participate in a research project.

Young children with physical disabilities who have difficulty producing speech are often reliant on using looking to communicate with others. For example, looking at a toy because they want to play with it. Some young children develop looking skills fairly easily, but for others it can be difficult.

Our study will test a number of looking-to-communicate skills in young children with physical disabilities.

The research is being carried out by the Developmental Science Department, University College London, in collaboration with Great Ormond Street Hospital. I am writing to you because your child is a patient of Great Ormond Street Hospital.

Your child's involvement in the research is described in the information sheet enclosed with this letter. Please take time to read it carefully. Talk to others about the study if you wish. This information sheet tells you about the purpose of the study and what will happen if you take part. It is important that you are clear about what participation means before you decide whether or not you are happy for your child to take part. If you have any questions, please do not hesitate to contact us.

If you would like your child to take part in the research, please complete the expression of interest form enclosed and return it in the envelope provided, and a member of the research team will contact you.

With best wishes

Michael Clarke   Katie Price   Tom Griffiths
                    Developmental Science Department, UCL

Appendix F-3 Information Sheet

INFORMATION SHEET
Early Social Communication Skills of Children with Cerebral Palsy

Dear _____

We would like to invite you and your child to take part in a research study. Before you decide, you need to understand why the research is being done and what it would involve for you. Please take time to read the following information carefully. Talk to others about the study if you wish. This information sheet tells you about the purpose of the study and what will happen if you take part.

Purpose of the study
Young children with physical disability who have difficulty producing speech are often reliant on using looking to communicate with others. For example, children might look at a toy because they want to play with it. Some young children develop looking skills for use in communication fairly easily, but for others it can be difficult.

Our study will explore a number of looking-to-communicate skills in young children with physical disabilities. Surprisingly, professionals don't yet have reliable ways of testing these skills in children with physical difficulties.

If we can find good ways of identifying children who struggle to develop looking-to-communicate skills, we hope that professionals (speech and language therapists, for example) will be able to work with children and their families more effectively.

We will use a number of simple activities that are easy to carry out and are suitable for young children with physical disabilities. These include seeing how children can move their eyes to show another person that they have seen some toys. We have attached a full description of the games and tasks for you to look at.

We will monitor how your child responds with their eyes to our activities; firstly, by just carefully observing their eye movements, and secondly by using state-of-the-art eye-tracking technology. There are no wires or physical connections involved in the eye-tracking technology. We will simply ask your child to look at a monitor (like a television screen) while the technology automatically tracks their eye movements. This technology has been used extensively with adults, children and babies.

Why has my child been invited to take part?
We are writing to you because you have previously visited a clinic within the Neurosciences directorate at Great Ormond Street Hospital, London.

You have been offered this information sheet because your child has been identified as meeting the criteria for inclusion in our project by your clinical care team at Great Ormond Street Hospital.

Please note that no one outside the care team at Great Ormond Street Hospital has had access to your personal details in preparing this invitation.

What would participation involve?
If you are willing for your child to take part in the study, we would like to invite you to University College London where we will carry out the activities to look at how children use their eyes for communication. A description of these activities is enclosed with this information sheet. After your visit we will provide you with a summary of how your child got on.

We appreciate that it can be an effort to travel in London with young children. We will be very happy to reimburse all your travel expenses, including use of taxis if this is helpful.

As Great Ormond Street Hospital is acting as a Participant Identification Centre only, no information will be recorded from your child's medical notes.

Will you video record my child?
Yes, with your permission we would like to video record the activities. This will help us to see accurately how your child gets on. It is important for you to understand how the recordings might be used, before agreeing that your child can take part. Two different sorts of consent can be given. We have called these: **research** participation, and **wider** participation:

- **Research participation** level of consent means that the video recordings will be used for the research study only.

- **Wider participation** level of consent means that video recordings might be used for teaching (e.g. undergraduate and postgraduate students, and health and education professionals), and at presentations outside University College London, such as international meetings. The videos could also be used in electronic publications such as CD-ROMs and web-based teaching and research resources.

It is important for you and your child to be comfortable with the level of consent that you give. You may change the level of consent or withdraw it completely at any time. However, we cannot accept liability if recordings have already been published. If you wish to alter the level of consent at any time, please telephone Michael Clarke at the Developmental Science Department, University College London (020 7679 4253).

Does my child have to take part?

It is up to you to decide. If, after reading this information sheet, you decide that your child can take part in the study, we will ask that you sign the enclosed consent form when you meet with the research team at UCL. You are welcome to ask any further questions you may have at this meeting.

If I agree to take part what will happen if I decide not to carry on?
It is important that you are aware that your participation in this study is strictly voluntary. You are free to withdraw your consent at any time without giving a reason. Withdrawing your consent will not affect your child's care.

Will taking part be kept confidential?
Yes. We will follow ethical and legal practice and all information about your child will be handled in confidence.

Very occasionally, UCL or other regulatory authorities may need to access data for monitoring or audit purposes. In this event, data will continue to be handled in the strictest confidence.

What will happen to the results of the study?
We will produce a report summarising how your child got on. We also aim to publicise our findings through journal articles and through presentations at conferences in the UK and abroad. Your child will not be identified explicitly in any publication or presentation.

Who is organising and funding the research?
The research is being organised by the Developmental Science Department, University College London. Great Ormond Street Hospital is acting as a Participant Identification Centre for this study. The study forms part of the course of two doctoral students, Katie Price and Tom Griffiths, who are based in the Developmental Science Department, University College London, and who are also clinical staff at Great Ormond Street Hospital.

Who has reviewed the study?
This research study has been looked at and given a favourable opinion by an independent group of people called a Research Ethics Committee to protect your safety, rights, wellbeing and dignity.

What if I have questions about the study?
Please do not hesitate to contact Michael Clarke at University College London (███ ████████████████████████████), Katie Price at ████████████████████ or Tom Griffiths at ████████████████████████ if there is anything that is not clear, or if you would like more information.

What if I have a problem with the study?
If you wish to complain, or have any concerns about any aspect of the way you have been approached or treated by members of staff or about any side effects (adverse

events) you may have experienced due to your participation in the research, the normal National Health Service or University College London complaints mechanisms are available to you. Please ask members of the research team if you would like more information on this. Details can also be obtained from the Department of Health website: http://www.dh.gov.uk.

In the unlikely event that you or your child is harmed by taking part in this study, compensation may be available. If you suspect that the harm is the result of the Sponsor's (University College London) negligence then you may be able to claim compensation. After discussing with the research team, please make the claim in writing to the Dr Michael Clarke who is the Chief Investigator for the research and is based at the Developmental Science Department, University College London (UCL), Chandler House, 2 Wakefield Street, London, WC1N 1PF. The Chief Investigator will then pass the claim to the Sponsor's Insurers, via the Sponsor's office. You may have to bear the costs of the legal action initially, and you should consult a lawyer about this.

What next?
If you are interested in taking part with your child after reading about the study, please return the enclosed expression of interest form in the envelope provided. We will then call you to discuss any questions you may have about the study and to arrange a time for you and your child to come to University College London to meet the research team. When you come to University College London we will be able to demonstrate the different activities we would like to carry out with your child, and if you are still happy for to take part we will ask you to complete a formal consent form (a draft consent form is enclosed with this information pack).

Best wishes

Dr Michael Clarke   Katie Price   Tom Griffiths
                  Developmental Science Directorate, UCL

Description of Activity	What will be required of my child?	How long will it take?
Observation of your child's motor abilities using a standard, published scale	Nothing. Observations will be made by the research team.	5 minutes
Observation of the type and distribution of cerebral palsy	Nothing. Observations will be made by the research team.	5 minutes
Intelligibility of your child's speech will be categorised using a published scale	Nothing. Observations will be made by the research team.	5 minutes
Intelligibility of your child's speech will be assessed through speech recordings as part of a published measure	Your child will need to repeat 50 words read out by an assessor.	10 minutes
Observation of your child's communication patterns will be made using an existing standard measure of their abilities as a receiver and giver of messages	Nothing. Observations will be made by the research team.	5 minutes
Assessment of language understanding and language use will be made using a standard measure, adapted for children with physical disabilities where necessary	Your child will be asked to look at toys and pictures as they are named by the assessor.	15 minutes
Assessment of your child's visual understanding (without language)	Your child will be asked to complete patterns in puzzles by looking at target pieces.	10 minutes
Assessment of your child's ability with general eye movement skills	Your child will be asked to look at a torch light as it moves across a screen.	10 minutes
A structured play session with a book, a puzzle and wind-up toys	Your child will play alongside the assessor with these toys.	10 minutes
Assessment of using eye gaze for communication will be made using a standard measure, adapted for children with physical disabilities where necessary	Your child will watch as the assessor presents toys, and have the opportunity to show with their eyes their observational and matching skills (for example, matching a miniature spoon to a large spoon).	15 minutes
Observation of how your child attends to biological motion (looking at a human shape as opposed to a random shape) will be carried out using eye-gaze technology	Your child will be asked to look at videos on a computer.	5 minutes
Observation of your child's response to noises in the environment	Your child's responses to a range of different noises will be noted.	5 minutes
Assessment of your child's understanding of other people's thinking	Your child will be asked to watch videos on a computer.	15 minutes
		115

29/07/13 version 2.0

5

Appendix F-4 Consent Form

UCL DEVELOPMENTAL SCIENCE DEPARTMENT	**Parent Consent Form CP v2.0**

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Early Social Communication Skills of Young Children with Cerebral Palsy

CONSENT FORM

Name of Chief Investigator: Michael Clarke

Please initial each statement below

1. I confirm that I have read and understand the information sheet dated 29th July 2013 (version 2.0) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

_____(1)

2. I understand that my child's participation is voluntary and that I am free to withdraw it at any time without giving any reason, without my legal rights or child's care being affected.

_____(2)

3. I consent to my child being video recorded as part of this study and I give **research participation** level of consent for the recordings.

_____(3)

4. I consent to my child being video recorded as part of this study and I give **wider participation** level of consent for the recordings.

_____(4)

5. I agree to my child taking part in the above study as described in the information sheet dated 29th July 2013 (version 2.0).

_____(5)

_____ _____ _____
Your name   **Date**   **Signature**

Michael Clarke   _____ _____
Researcher   **Date**   **Signature**

Appendix F-5 Functional Vision Behavioural Score Sheet

Behavioural Test Score Sheet

Child ID: _____ Date: _____
Distance from display: _____

Gaze Fixation Task

Stimuli appears on my:	Time to fixation (s) (3= immediate, 2= within 2s, 1= 3-6s, 0= more than 6s)	Gaze orientation?	2 second fixation?	Prompts given (TICK)			
				VERBAL	LIGHTS	MOVEMENT	OTHER
1. LEFT	3 2 1 0	1 0	1 0				
2. CENTRE	3 2 1 0	1 0	1 0				
3. RIGHT	3 2 1 0	1 0	1 0				
4. BOTTOM	3 2 1 0	1 0	1 0				
5. CENTRE	3 2 1 0	1 0	1 0				
6. RABBIT							
7. BOTTOM	3 2 1 0	1 0	1 0				
8. LEFT	3 2 1 0	1 0	1 0				
9. TOP	3 2 1 0	1 0	1 0				
10. RABBIT							
11. RIGHT	3 2 1 0	1 0	1 0				
12. TOP	3 2 1 0	1 0	1 0				

TOTALS
Total number of gaze orientations = _____ /10
Average time to fixation= _____

Total number of 2 second fixations= _____ /10
Overall Score= _____ /20

Other Notes
e.g. prompts given, patterns of error

'Overlap' Task (block 1)

Trial	2nd stimuli appears on my:	B/G/O	Time to fixation on 2nd stimuli (s) (2= within 2s, 1= 3-6s, 0a= nil initial fixation, 0b=nil shift, 0c= shift from all stimuli)	Prompts given (TICK) VERBAL	LIGHTS	MOVEMENT	OTHER
1.	Left (s)	O	2 1 0a 0b 0c				
2.	Left (f)	B	2 1 0a 0b 0c				
3.	Right (s)	B	2 1 0a 0b 0c				
4.	Right (f)	O	2 1 0a 0b 0c				
5.	Left (f)	O	2 1 0a 0b 0c				
6.	Left (s)	B	2 1 0a 0b 0c				
7.	Right (f)	O	2 1 0a 0b 0c				
8.	Right (s)	B	2 1 0a 0b 0c				

'Overlap' Task (block 2)

Trial	2nd stimuli appears on my:	B/G/O	Time to fixation on 2nd stimuli (s) (2= within 2s, 1= 3-6s, 0a= nil initial fixation, 0b=nil shift, 0c= shift from all stimuli)	Prompts given (TICK) VERBAL	LIGHTS	MOVEMENT	OTHER
9.	Left (s)	O	2 1 0a 0b 0c				
10.	Left (f)	B	2 1 0a 0b 0c				
11.	Right (s)	O	2 1 0a 0b 0c				
12	Right (s)	B	2 1 0a 0b 0c				
13.	Left (s)	O	2 1 0a 0b 0c				
14.	Left (f)	B	2 1 0a 0b 0c				
15.	Right (f)	O	2 1 0a 0b 0c				
16.	Right (f)	B	2 1 0a 0b 0c				

Other Notes