The association of early touchscreen media use with the development of visual attention and executive function

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Declaration

I, Ana Maria Portugal, confirm that the work presented in this thesis is my own.

Exception: A part of the data reported in this thesis (12 and 18 months visits) was collected by Dr. Celeste Cheung during her Post-Doc on the TABLET project under the supervision of Dr. Tim J. Smith. During my PhD I followed up the same group of children, administering additional tasks when the children were 3.5 years old. The pre-processing and analysis of all datasets (including the previously collected eye-tracking data) were performed by me. Specifically this involved:

- Preparation and analysis of longitudinal data relating to attentional control from the TABLET Study, including writing of automatic algorithms for detection of reaction times and saccades to stimuli and validation of trials for Chapter 3 and 4;
- Design and administration of a battery of Executive Function tasks suitable for children and preparation and analysis of data, including arranging and piloting EF tasks with 10 toddlers, supervising the video-coding of outcome measures and trial validity for the EF tasks, and writing of automatic algorithms for computation of average scores for the screen-based EF tasks;
- Follow-up contact and experimental data collection (including the data for the attention control and EF battery presented in this thesis) for the 3.5-year visit of the TABLET project using eye-tracking, behavioural, activity and physiological, vision ophthalmic and standardised Mullen Scales of Early Learning assessments, having been trained in all of these measures. I tested 47 3.5-year-olds recruited for the study.

Additionally, I helped Dr. Celeste Cheung test 18 12-month-olds and 12 18-month-olds for the study. I analysed and interpreted all data for the empirical chapters in this thesis, under the guidance of my supervisors. I designed and illustrated/prepared all the figures in this thesis, except stated otherwise in the figure caption.

Signed:

Wednesday, February 19th, 2020

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Dedicado às minhas avós / For my grandmothers

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Abstract

Attention plays a pivotal role in information processing by filtering the potential information available based on individual goals, states, and past experiences. Early attention control is thought to underpin and support executive functions (EFs), which in turn are predictive of later behavioural outcomes. The development of attention and EF is partly subject to environmental influences, such as the use of digital media. There is a rapid increase in accessibility and usability of mobile touchscreen devices (i.e. smartphones and tablets) in the family environment, but rigorous scientific research investigating the impact on the developing mind lags behind the widespread usage. To address this, children with different levels of touchscreen use were followed longitudinally at 12 months, 18 months, and 3.5 years, and tested on attention control (bottom-up, and top-down), and EF (updating, shifting, and inhibiting).

Children with high touchscreen use were faster on single (i.e. pop-out) visual search, with the amount of concurrent use associated with the speed of bottom-up attention in a linear manner. This saliency bias was repeatedly found on saccadic control tasks, where steady longitudinal high use was associated with a quickening of attention to peripheral salient onsets with a resulting detriment to top-down performance, i.e. disengagement and inhibition of attention. Finally, top-down difficulties were also seen in EF tasks in high users at 3.5 years, particularly in processes of updating and shifting between abstract mental sets.

These results point to an influence of touchscreens use on the emerging attention and EF systems, in a way that experience of salient and contingent digital content elicits automatic biases to bottom-up processing, and displaces competency of top-down control and/or increases reliance on stimulus-response pairings. Future studies are needed to demonstrate causality, and to understand long-term trajectories and the interplay between bottom-up and top-down processes over time.

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List of Abbreviations

ADHD: Attention deficit/hyperactivity disorder

ANOVA: Analysis of variance

AOI: Area of interest

AVG: Action Video Games

CBQ: Children's Behavior Questionnaire

CF: Cognitive Flexibility

CFA: Confirmatory Factor Analysis

DCCS: Dimensional Change Card Sorting

ECBQ: Early Childhood Behavior Questionnaire

EF: Executive Function

EFA: Exploratory Factor Analysis

GEE: Generalized Estimation Equation

IBQ: Infant Behavior Questionnaire

IC: Inhibitory Control

ICC: Intra-class correlation coefficient

ms: Milliseconds

MSEL: Mullen Scales of Early Learning

RMSEA: Root Mean Squared Error of Approximation

RT: Reaction Time

SD: Standard Deviation

SEM: Structural Equation Modelling

TABLET: Toddler Attentional Behaviours and LEarning with Touchscreens

TV: Television

UK: United Kingdom

US: United States

WM: Working memory

Chapter 1:
General Introduction

1.

Attention plays a crucial function during development for at least two reasons: 1) it supports mechanisms of online regulation which enable increasing selectivity by internally directed or goal-driven processes over exogenous ones (i.e. driven by external perceptual characteristics); and 2) attentional maturation differences will, through a system of cascading effects on response and action over time, indirectly gate the development of other cognitive functions, particularly executive function, which in turn are predictive of general intelligence and academic achievement (Blair & Razza, 2007; Diamond, 2013; Mulder, Hoofs, Verhagen, van der Veen, & Leseman, 2014; Rueda, Checa, & Rothbart, 2010), and long-term wellbeing and success (Diamond, 2013; Hughes, 1998; Moffitt et al., 2011; Rose, Feldman, & Jankowski, 2012; Rueda et al., 2010). Although under tight genetic control (Fan, Wu, Fossella, & Posner, 2001; Friedman et al., 2008; Kennedy et al., 2017; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005; Scerif & Wu, 2014; Siqueiros Sanchez et al., 2019), the development of executive function processes (including attention control) are thought to be susceptible to environmental influences (Conejero & Rueda, 2017; Diamond & Ling, 2016; Hendry, Jones, & Charman, 2016; Posner, Rothbart, Sheese, & Voelker, 2012; Rueda et al., 2005; Scerif, 2010). This is because the neural networks and structures that subserve attentional control and executive functioning are very unspecialised and undifferentiated earlier in development (Fiske & Holmboe, 2019), so might be more vulnerable to external influences that alter their developmental trajectory as an adaptive response (Johnson, Jones, & Gliga, 2015; Wass & Scerif, 2012; Werchan & Amso, 2017). Also, early environmental deviations to attention and executive control can have more widespread effects (outside the cognitive function primarily influenced) later in development by evoking cascading effects of changes across domains (Johnson, 2012; Johnson et al., 2015; Karmiloff-Smith, 2009; Scerif, 2010; Scerif & Karmiloff-Smith, 2005). One factor that investigators, parents, and practitioners, have hypothesized to influence attention and executive function development is the visual experience of screen media activity (Bavelier, Green, & Dye, 2010; Christakis, 2016; Kostyrka-Allchorne, Cooper, & Simpson, 2017a; Nikkelen, Valkenburg, Huizinga, & Bushman, 2014; Rothbart & Posner, 2015; Wilmer, Sherman, & Chein, 2017). The infant and toddler use of mobile touchscreen digital media (e.g. tablets, smartphones) is increasing rapidly (tablet use increased from 28% to 58% between 2013 and 2018; Ofcom, 2019) with daily usage as young as 6 months of age (Bedford, Saez De Urabain, Cheung, Karmiloff-Smith, & Smith, 2016). As the time young children spent with digital media increased, so have popular and clinical concerns about its possible relations with children's health and well-being (Bell, Bishop, & Przybylski, 2015), including with attention deficit/hyperactivity disorder (ADHD)-like behaviours (Carr, 2011; Christakis, 2016). While official guidelines (e.g. AAP Council on Communications and Media, 2016) generally advise no screen time for infants and toddlers, based on empirical evidence from television suggesting that high levels of screen time may be associated with attentional and executive problems (Christakis, Zimmerman, DiGiuseppe, & McCarty, 2004; Kostyrka-Allchorne, Cooper, & Simpson, 2017a; Nikkelen et al., 2014); developmental experts see modern touchscreen technologies as a potential source of attractive and educational stimulation (Bavelier et al., 2010; Christakis, 2014; Geist, 2014; Zimmermann, Moser, Lee, Gerhardstein, & Barr, 2017). Scientific evidence in support of any of these views that could inform policy-makers and parents is lacking. To fill this gap, in this thesis, I present a set of studies investigating the longitudinal association between young childhood touchscreen use and the development of attention control and executive function.

The three most important concepts in the current thesis are attention control, executive function, and (touch)screen media use. The three of them suffer from unsatisfactory definitions in the literature and several authors have challenged their unitary conceptualisation. Therefore, in this introductory chapter, I aim to briefly outline the literature and inconsistencies surrounding each one, define them and how they are operationalised in the studies presented in this thesis, and explain how they are connected. I will also present a review of studies considering both attention and executive function in relation to digital media exposure; most of which I will only provide an overview of in the later chapters.

1.1. Attention control and executive function

1.1.1. Attention: perceptual processing bottleneck

Attention is a multidimensional construct that serves as a mechanism to systematically sustain and shift attentional focus (either to an external object or an internal thought). It works by means of maintaining an optimal level of performance and balancing sensory input sensitivity and internally-driven guidance. Attention models focus on related but distinct functions (e.g. alerting, orienting, and executive) that are part of the attention skill-set, and that can be influenced, moment-by-moment, either by endogenous (internal drives or goals) or by exogenous (environment physically salient events) factors.

According to Posner and Petersen's attention system model (Petersen & Posner, 2012; Posner & Petersen, 1990) three main brain networks support specific attentional functions.

- The Alerting attentional network functions to support the initiation and maintenance of an optimal state of attention. It can be distinguished in terms of phasic processes (response readiness and vigilance elicited by a warning cue) or intrinsic processes (a general regulation of arousal, e.g. prolonged sustained attention). In very young infants (up to 3 months postnatal), alertness is usually initiated by exogenous events (e.g. Wolff, 1965) or by lower-level mechanisms of arousal (e.g. feeding or tactile stimulation; Karmel, Gardner, & Magnano, 1991).
- The Orienting attentional network is related to the process by which attention is directed towards a selected stimulus for priority processing and encoding (Posner, 1980), often seen as bottleneck or filtering process. It allows detection, localization, and selection (e.g. bringing the target of selection to the fovea) in an array of sensory input. In visual attention, this function is intimately related to oculomotor functions, because they support the overt engagement of attention to a particular location (by means of holding a fixation) and the disengagement and shifting of attention locus (by means of saccadic eye movements; Colombo, Mitchell, Coldren, & Freeseman, 1991; Corbetta et al., 1998).
- The Executive attentional network's primary function is one of a mechanism of control. A critical ability of this network is to regulate inhibition and activation of the attentional response to a stimulus, event, or task at hand; but it also includes conflict resolution, error monitoring, resources management between bottom-up and top-down, activation of non-dominant responses/ overcoming of automatic or rewarding responses, and generation of novel responses. Its construct overlaps considerably with the ones of top-down attention control, executive functioning, and effortful control (Conejero & Rueda, 2017; Rothbart, Sheese, & Posner, 2007).

While the executive network appears to be functional as early as 4 months of life, it follows a protracted trajectory that extends throughout childhood well into adolescence and young adulthood (Colombo et al., 1991; Conejero & Rueda, 2017). In contrast, alerting and orienting processes are stable and adult-like by early childhood (Colombo et al., 1991).

Through these networks, visual attention filters out sensory visual input that proceeds to memory and output execution systems, acting as a crucial processing bottleneck, which is particularly important for learning and adaptive behaviours. It is thought that attention selection and regulation can, at a given moment in time, be driven by **exogenous** or **endogenous** factors.

Exogenous attention is usually related to transient, stimulus-driven, and bottom-up visual exploration. It is often seen in terms of a physiological reflex (expressed through a reflexive saccade) to environmental stimuli and events, for example to movements, high-pitch sounds, and low-level perceptual features of face-like stimuli (Cassia, Valenza, Simion, & Leo, 2008). There is a consensus in the visual attention literature that, as a more automatic process governed by subcortical structures thought to be minimally plastic, exogenous attention is less amenable to change from altered experience (Hubert-Wallander, Green, Sugarman, & Bavelier, 2011b). However, these views can benefit from further exploration and a new research argument has been put forward that delineates a parallel between exogenous and past-selection-driven attention (see below).

Exogenous aspects of attention are thought to emerge very early in development (even before birth), and to be relatively well developed and in an adult-like state at an early age (i.e. at least before the age of 5; Iarocci, Enns, Randolph, & Burack, 2009). But exogenous attention seems to play a specific key role in the first months of development: by triggering orienting to perceptually salient features (e.g. faces, toys), builds experience with said objects, and shapes attentional bias and learning, with subsequent cascading effects in other domains of development. Over the ages of 4 to 8 months exogenous cues start to have a decreasing influence as the infant needs to start being able to release their attention from environmental constraints, while individual attentional bias and own goals and interests have an increasing influence (Frank, Vul, & Johnson, 2009; Frank, Vul, & Saxe, 2012; Kwon, Setoodehnia, Baek, Luck, & Oakes, 2016; Werchan, Lynn, Kirkham, & Amso, 2019). In adults, exogenous attention is of relatively less importance and often acts as a circuit breaker of endogenous attention, allowing for rapid re-orienting to peripheral salient unexpected cues (Kim, 2014).

Endogenous attention describes sustained, task-focused, and top-down visual exploration (Chica, Bartolomeo, & Lupiáñez, 2013), which is influenced by context, expectations, and associations learned over time. By the second year of life, endogenous attention is primarily supported by the aforementioned executive attention network, and it is related to functions of disengagement of attention, inhibition of distracting stimuli, and serial processing; capacities which progress slowly throughout development (Davidson, Amso, Anderson, & Diamond, 2006). This top-down selection of attention is often related to selection based on past experiences and their associated spatial memories (but see below a discussion on the current debate). Though the neural systems underlying endogenous processes are generally thought to be complex and slow to mature, recent findings suggest that memories, as an endogenous factor, may play a particularly important role in shaping attention early in life (Nussenbaum, Scerif, & Nobre, 2018).

Converging evidence suggests that bottom-up and top-down are two attentional systems that operate independently (Chica et al., 2013; Pinto, van der Leij, Sligte, Lamme, & Scholte, 2013). Over the first few years of life, there is a shift from a primarily exogenous-driven attentional style to a more internally-controlled attentional one. However, it is still unclear how, throughout the lifespan, salient events and individual factors *compete* or *cooperate* to influence where attention is oriented to guide adaptive behaviour (Nussenbaum et al., 2018). Recent work in this area paints a complex picture of the interplay between attentional capture, experience, and context, but also creates debate around the line that separates the two processes.

Attention researchers usually argue that top-down selection includes everything that is not bottom-up (Gaspelin & Luck, 2018), but some researchers have been arguing for a new type of mechanism, different from top-down attention, dedicated to history-driven selection (Awh, Belopolsky, & Theeuwes, 2012; Theeuwes, 2019). History-driven (or selection-history, or experience-driven) attention would share key properties with bottom-up attention, such as attentional capture (faster latencies, low effort, and competition with current task-goals) towards past-selected objects, locations, or stimuli features (e.g. attention to learned regularities); and would be supported by different brain regions than stimulus-driven and goal-driven selection (Theeuwes, 2019) – see Figure 1.1. Practical examples of effects implicated in this selection-history attention are associative learning (including value/reward learning; B. A. Anderson, Laurent, & Yantis, 2011; Failing & Theeuwes, 2017) and statistical learning of environment regularities (B. Wang & Theeuwes, 2018a; 2018b), priming phenomena (Kristjánsson & Campana, 2010), or contextual cueing (Chun & Jiang, 1998; Geyer, Zehetleitner, & Muller, 2010). These effects have also been shown in children; for example, school-aged children have been found to have similar contextual cueing effects as adults, and search for a target among distractors in old display arrays faster than in new display arrays, due to previous experience with the characteristics of those arrays (Dixon, Zelazo, & De Rosa, 2010). Another interesting example is the case of adults who, as children, had extensive visual experience with the video-game *Pokémon* (a popular game in the 90s that entailed repeated, prolonged and rewarded experience with animal-like pixelated characters); these adults' early extensive visual experience resulted in much later selective responses and distinct visual cortical specialization (lateral to face-selective regions) for *Pokémon* stimuli (an artificial category; Gomez, Barnett, & Grill-Spector, 2019). In another study, memory-guided attention, as a selection-driven process, seemed to be stronger than exogenous cues in children (Nussenbaum et al., 2018). This could be due to a higher reliance on past experiences to guide attention early in development (either because children have more rigid representations of episodic memories or as a form of adaptive behaviour to the environment) or to a more efficient integration between top-down, bottom-up, and selection-history factors in adulthood (Franchak, Heeger, Hasson, & Adolph, 2016; Nussenbaum et al., 2018). Overall, and putting aside contemporary debates and terminology matters, the studies presented highlight that adults and children rely on associations they learn through experience over time to shape their subsequent attentional patterns, both in the short term (like in contextual cueing) or long-term (the *Pókemon* case), using their sensitivity to statistical regularities of the visual environment and memory of previous experiences to guide attention deployment and allocation.

By shaping perceptual bias and orienting processing to relevant content, attention plays a fundamental role in learning from and adapting to the environment, particularly during the first few years of life. The study of how attention develops and how this impacts other cognitive functions and general child development is thus of particular interest to developmental science studies.

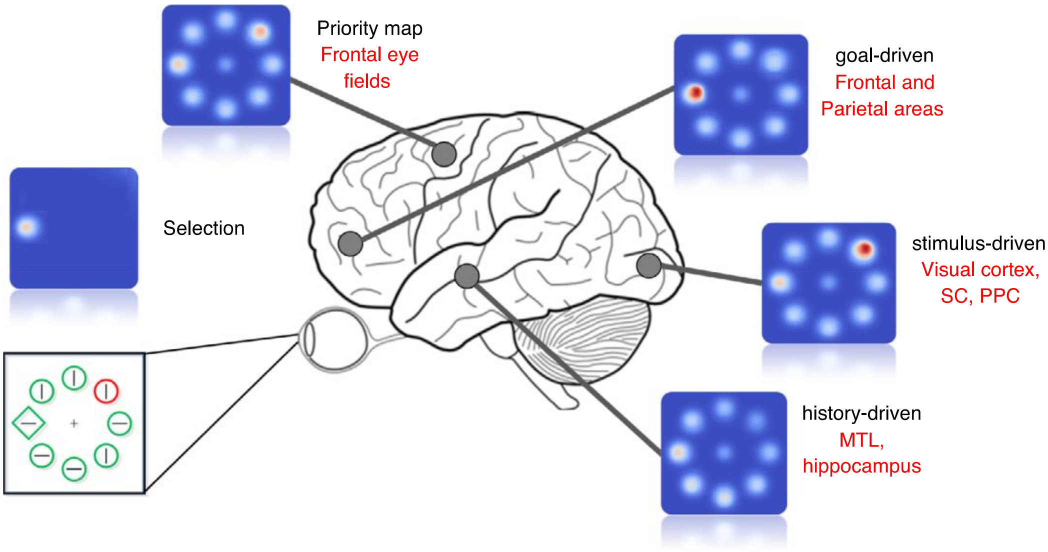

Figure 1. 1. Schematic overview of the different factors and brain regions involved in history-driven selection. Adapted from "Goal-driven, stimulus-driven, and history-driven selection" by J. Theeuwes, 2019, Current Opinion in Psychology, 29, p. 98.

1.1.2. Attention: early development and emergent executive abilities

During the first 6 months of life, attention orienting overlaps quite a lot with the development of the visual system, when a rapid improvement occurs in fundamental visual abilities such as acuity, accommodation, binocularity, and oculomotor control (Atkinson, 1984). Changes in visual orienting can be seen in terms of increasing maturation of the oculomotor control neural networks and pathways. Before 3 months of age, attention in the infant is essentially reactive to exogenous events and low-level perceptual features and characterised by a prominent inhibitory role of the superior colliculus in "sticking" visual attention. It is not until cortical inhibitory functions emerge, resulting from the maturation of frontal cortex regions, such as the frontal eye fields, that the proportion of automatic or reflexive saccades changes relative to voluntary or targeted saccades (Johnson, 1995; 2002; Richards & Hunter, 1998). After this achievement, infants quickly start to internally deploy attention: this manifests around 2 to 4 months, when infants start demonstrating some primary mechanisms of endogenous control, like disengagement of gaze from already explored objects (Hood & Atkinson, 1993; Johnson, Posner, & Rothbart, 1991), anticipatory eye movements (Haith, Hazan, & Goodman, 1988), and contingency learning (i.e. using cues to predict spatial location of targets; e.g. Hood & Atkinson, 1993; Johnson et al., 1991; Johnson & Tucker, 1996; Posner, Rothbart, & Thomas-Thrapp, 1997). With time, they also acquire the ability not only to voluntarily shift their gaze to interesting stimuli, but to inhibit orienting to irrelevant or distracting stimuli (e.g. avoiding pro-saccades abilities at 4 months; Johnson, 1995; Scerif et al., 2006), and to selectively inhibit distractors at 9 months (Holmboe, Pasco Fearon, Csibra, Tucker, & Johnson, 2008). Infants still have little control over their allocation of attention but the abilities to flexibly shift and inhibit attention continue to develop throughout the first years of life along their integration with other processes and functions; and toddlers become increasingly competent in controlling attention across modalities and in situations that require more complex behaviours (such as in visual tasks that require conflict resolution, double-step actions like anti-saccades, sensorimotor integration, or abstract maintenance of goals and rules). These abilities are seen as a demonstration of the emergent executive system (Colombo & Cheatham, 2006; Conejero & Rueda, 2017; Courage, Reynolds, & Richards, 2006; Ruff & Rothbart, 1996). Beyond infancy, the neural networks for eye movements and attentional processes largely overlap (Corbetta et al., 1998; Hutton, 2008).

Increasing research indicates that attention control is important for later social adjustment and academic performance (Papageorgiou et al., 2014; Rueda et al., 2010), and it is also implicated in a range of developmental disorders such as Autism Spectrum Disorders (ASD; Bedford et al., 2012; Elsabbagh et al., 2013; Hendry et al., 2018; Wass et al., 2015) or ADHD (Barkley, 1997; Munoz, Armstrong, Hampton, & Moore, 2003; Tseng et al., 2012). For example, difficulties with attention disengagement have been found in children at-risk for ASD (Elsabbagh et al., 2013); whereas difficulties with suppression of automatic saccades have been associated with the ADHD phenotype (Barkley, 1997).

Managing where to attend to is critical for infants and toddlers learning and socio-cognitive development, for example when learning the names of objects from a caregiver in the presence of distracting toys (Yu, Suanda, & Smith, 2019), people (Wass et al., 2018), or screens (Schmidt, Pempek, Kirkorian, Lund, & Anderson, 2008). For this reason, attentional control has been seen as an important hub for cognitive functions (Astle & Scerif, 2009; Scerif, 2010), and a “gate” for the acquisition of other cognitive skills, such as EFs (Hendry et al., 2016), and self-regulation (Conejero & Rueda, 2017; Rothbart et al., 2007).

In this thesis, attention will be restricted to the visual domain and operationalized in terms of overt shifts of attention based on gaze behaviour. It will be dissociated in terms of **exogenous** and **endogenous** processes (as described above), where exogenous attention will be operationalized in terms of oculomotor latencies to orient attention to salient targets and distractors in no competition scenarios; and endogenous attention will be related to top-down goal-driven processes and operationalized in terms of oculomotor metrics related to serial orienting abilities and executive abilities to disengage and inhibit attention.

In the sections below, I will review studies investigating the associations between digital media experiences and attention development. In these studies, attention is typically measured either directly by observational measures (e.g. sustained attention to toys), or indirectly through parent- or teacher-reported questionnaire measures of everyday attention functioning and difficulties, often associated with ADHD traits. Although past literature suggests that performance-based measures of executive attention and parent-ratings of attention problems are associated (Carlson, Mandell, & Williams, 2004a; Geeraerts et al., 2018; Gerardi Caulton, 2000; Joyce et al., 2016; Kochanska, Murray, Jacques, Koenig, & Vandegeest, 1996), it should be noted that questionnaire-based measures are best viewed as measures of effortful attention sustained by the executive attention system. This system greatly overlaps with the broader construct of Executive Functions (EF), which I will introduce below.

1.1.3. Executive Function: organisation

Executive Function (EF) is an umbrella term given to the set of cognitive processes involved in the top-down regulation of cognition and behaviour. It is seen as a general-purpose control mechanism that modulates cognition (Miyake et al., 2000) and supports goal-directed (Zelazo & Frye, 1998), flexible (Munakata, 2001), and novel (in opposition to automatic or habitual responses; Diamond, 2013) actions and thoughts. Evidence from neuroimaging and from neuropsychological studies of patients with prefrontal lesions have indicated that different EF processes have differential connections with areas of the prefrontal cortex (V. Anderson, Levin, & Jacobs, 2002; Eslinger, Biddle, & Grattan, 1997). EF was previously thought not to be functional before later childhood (Hughes, 2002), but recent developmental studies (including research employing neuroimaging and child-friendly behavioural methods) has contributed hugely to the study of early life EF by demonstrating a wide range of abilities in infancy and early childhood that are seen as fundamental precursors of EF, by underpinning the emergence of its major constructs and contributing to shape its later structure (Fiske & Holmboe, 2019; Hendry et al., 2016). The development of EF is strongly associated with the maturation of the prefrontal cortex, which is one of the brain areas developing slowest (Benes, 2001; Diamond, 2002; Fiske & Holmboe, 2019; Werchan & Amso, 2017).

One of the most influential models of EF dissociates performance in three separate but related constructs (the *unity-yet-diversity* model; Diamond, 2013; Friedman et al., 2006; Miyake et al., 2000), which are working memory, inhibitory control, and cognitive flexibility. These are briefly described below and in more detail in Chapter 5.

Working memory (WM) or *updating* is the process whereby relevant information is temporarily held and updated in mind to guide ongoing responses. Of all EF constructs, WM is the one which is thought to have more overlapping brain and behaviour correlates with attention control (Amso & Scerif, 2015; Scerif, 2010; Wass, 2014a; Wass & Scerif, 2012), particularly early in development (Scherf, Sweeney, & Luna, 2006).

Inhibitory control (IC) or *inhibition* is the controlled and deliberate suppression of automatic or dominant responses and thus is better viewed as a function to regulate efficiently activation-inhibition of responses. The unitary view of this construct is challenged by the consistent difficulty in finding robust correlations between conventional inhibitory control tasks (e.g. Go/No-go, Anti-saccade, Snack delay; Carlson & Moses, 2001; Gärtner & Strobel, 2019; Murray & Kochanska, 2002), which lead some authors to dissociate IC in terms of direct (global, "Don't do X") or indirect (competitive, "Do Y" representations) forms (Munakata et al., 2011), or in terms of IC strength and endurance demands (e.g. Snack delay tasks, to wait for a treat, demand relatively weakly IC but for a longer period of time; whereas Go/No-go type tasks require brief but demanding suppression/activation control of a dominant response; Simpson & Carroll, 2019). Another common distinction lies between cool and hot EF, based on whether a problem involves abstract versus motivational aspects. Hot executive control refers to performance that occurs in emotionally arousing and highly motivating contexts, involving a very salient reward such as sweets; cool executive functioning refers to regulation that occurs in neutral contexts such as selecting stimuli in presence of distractors or inhibiting a habitual response. Although this distinction can be applied to EF more broadly, it is often used to dissociate IC performance on measures of inhibition of pre-potent responses (e.g. Go/No-go) and inhibition in the context of delay gratification (e.g. the Snack delay task), because performance on tasks like Go/No-go (cool-IC) and delay of gratification tasks (hot-IC) are consistently uncorrelated in developmental literature.

Cognitive flexibility (CF) or *shifting*, is usually seen as the ability to switch between mental sets (i.e. engagement/disengagement of task-set representations), but also includes resolving conflicts arising from proactive interference from prior task sets (Miyake et al., 2000). Of the three constructs presented, cognitive flexibility is the one emerging latest during development.

The field has advanced considerably since Miyake's (2000) proposed model. Some authors have argued for the addition of other dissociable EF processes, including the addition of a separable component of selective attention (Fournier-Vicente, Larigauderie, & Gaonac'h, 2008). Miyake and colleagues (2012) have updated their model since, and now place adult EF organised around a Common EF factor and separate *updating* and *shifting* specific factors (Miyake & Friedman, 2012). This Common EF is seen as an ability of maintenance and management of timely relevant goals to regulate which functions or networks are deployed; it has been hypothesized to be *inhibition* (Miyake et al., 2000), or even top-down attentional control (Garon, Bryson, & Smith, 2008; Miyake et al., 2000). Indeed, the three EFs seem to be strongly bound to the executive attention system, particularly during development – see section 1.1.4 below.

Studies with older children have generally supported a three subcomponents model of EF structure, at least from 7 years of age (Best & Miller, 2010). However, in early childhood, a dissociable pattern of EF abilities is less clearly evident, likely because EF processes are not yet fully functional and integrated. Many researchers have found that a unitary EF factor best represents EF organisation in pre-school years (e.g. Hughes, Ensor, Wilson, & Graham, 2009; Shing, Lindenberger, Diamond, Li, & Davidson, 2010; Wiebe, Espy, & Charak, 2008), although more recent studies have detected dissociable EF latent factors in children aged 2 to 3 years-old (Bernier, Carlson, Deschênes, & Gagné, 2012; Garon, Smith, & Bryson, 2014; Mulder et al., 2014). Built upon current developmental views of EF (Garon et al., 2008; 2014) and collected evidence, a recent model for EF organisation across development has been conceptualised by Hendry and colleagues (Hendry et al., 2016). Their model includes foundational abilities (i.e. attention control, self-regulation, processing speed, and crude cognitive flexibility) that, in interaction with each other, drive and constrain EF development in the first three years of life, by supporting the emergence of EF and becoming integrated into more complex EF skills – see Figure 1. 2. While during the first year only foundational abilities are observable, or at least are in someway measurable; by the end of the third year EF structure starts to resemble adult-like functioning, with impulse control (i.e. inhibition in terms of self-regulatory mechanisms) and cognitive flexibility (i.e. cognitive control, encompassing both updating and shifting) as pillars.

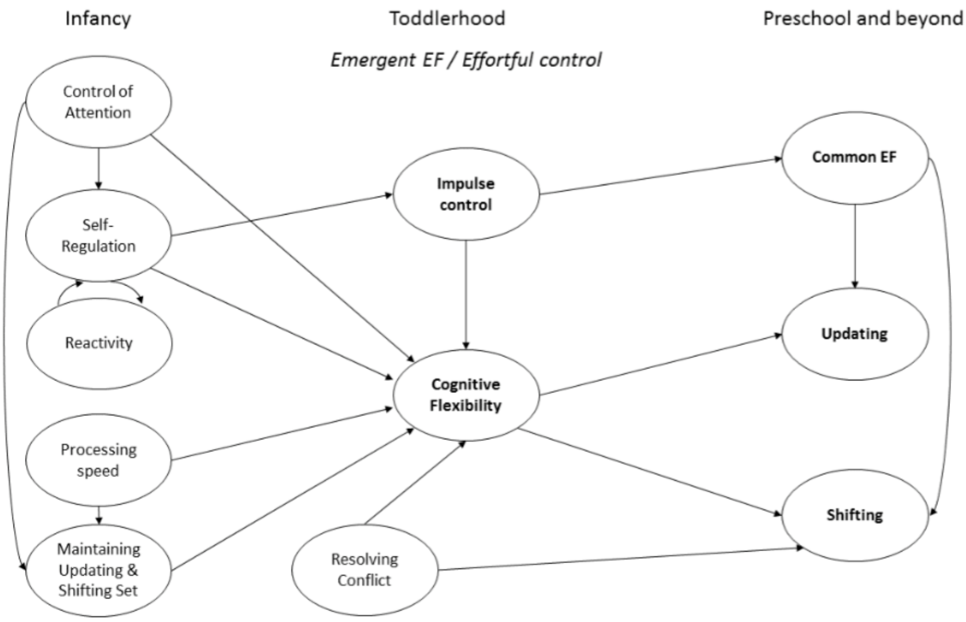

Figure 1. 2. Hendry and colleagues' conceptual model of the development of Executive Function. Adapted from "Executive function in the first three years of life: Precursors, predictors and patterns" by A. Hendry, E. J. H. Jones, and T. Charman, 2016, Developmental Review, 42, p. 3.

To avoid overlapping between attention control (a foundational EF ability in the model just presented) and executive functions, in this thesis, EF will be, initially, described as a skill-set of three separate but related processes. It is operationalized by lab-based cognitive measures tapping into each of the three separate components: working memory, inhibition, and cognitive flexibility. In the digital media literature presented below, EF is typically measured as a composite (following up on a unitary view of EF); I will whenever available, specifically address the components included.

However, before describing the literature on digital media influences on attention and EF, I will briefly acknowledge the associations between attention control and EF, given that it is generally agreed that their interplay is fundamental in development.

1.1.4. Individual differences in attention and its relationship to Executive Function

During the first months of life, infants can only select visual objects, attend to, and track, before they are able to reach and move to the objects. This period of exploration through attention forms the cognitive foundation of subsequent deliberate action, and thus attention has been widely viewed as pivotal to the construct of a central brain executive control system (Baddeley, 2002; Conejero & Rueda, 2017; Garon et al., 2008; Kane &

Engle, 2003; Posner & Rothbart, 2007), and one cannot fully understand EF without considering attention control. The control of attention, specifically endogenous attentional control, is seen as a pre-requisite, a supporter, and a drive for EF.

The executive attention network undergoes major improvements during and before the pre-school period (Conejero & Rueda, 2017; Garon et al., 2008; Rueda, Posner, Rothbart, & Davis-Stober, 2004b). This executive network has been found to include the anterior cingulate cortex, the lateral ventral prefrontal cortex and the basal ganglia, and is modulated by dopamine (Posner & Fan, 2008). Interestingly, these areas overlap substantially with the regions found to be active during WM tasks (Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006; Scherf et al., 2006), and other EFs (Fiske & Holmboe, 2019; Rothbart et al., 2007; Rothbart & Posner, 2006).

The early abilities in the processes of visual allocation have been suggested to be a necessary first step towards the emergence of EF, i.e. to form a foundation for the development of EF skills (Garon et al., 2008; Hendry et al., 2016), because they are predictive of later executive skills. During the first months of life, orienting to stimuli and shifting gaze abilities (sustained looks, fixation durations) are predictive of inhibitory control, cognitive flexibility and working memory skills throughout childhood (Cuevas & Bell, 2014; Papageorgiou et al., 2014; Rose et al., 2012). Around the first birthday, infants' sustained attention during free-play is also a predictor of later inhibitory control and cognitive flexibility (Johansson, Marciszko, Gredebäck, Nyström, & Bohlin, 2015; Kochanska, Murray, & Harlan, 2000; Ruff & Lawson, 1990). Differences in attention control in infancy have also been shown to predict pre-schoolers delay of gratification (Sethi, Mischel, Aber, Shoda, & Rodriguez, 2000). Besides, other attentional abilities acquired before the first birthday (inhibitory looking behaviours, and selective inhibition of looking) predict conflict resolution (an emergent EF in Hendry's model of EF development) later in toddlerhood (Holmboe et al., 2008). For that reason, in contemporary models of EF development, attention control plays a critical role in its organisation (see Figure 1. 2).

Besides the role as a supporter and drive, many contemporary models of EF include or mention attention control as a common component involved in all EF operations (e.g. Garon et al., 2008; Miyake et al., 2000; Miyake & Friedman, 2012). However, other researchers argue that attention control is specifically a core component of working memory (Amso & Scerif, 2015; Astle & Scerif, 2011; Cowan & Morey, 2006; Kane & Engle, 2002; Klingberg, Forssberg, & Westerberg, 2002), suggesting that it is the convergence of the two processes in the early years that later lead to the emergence of other EF skills during pre-school (Fiske & Holmboe, 2019).

Nevertheless, evidence indicates that performance on all constructs of EF is strongly associated with concurrent and earlier performance of the executive attention system (Blankenship et al., 2019; C. Cheng, Kaldy, & Blaser, 2019; Cuevas & Bell, 2014; Engle:1990up; Kane, Bleckley, Conway, & Engle, 2001; Veer, Luyten, Mulder, van Tuijl, & Sleegers, 2017). For example, less distractible infants can focus and fixate their attention on an object location for longer delays in the delayed response task (an infant measure of working memory; Diamond & Doar, 1989), and differences in attention control differentiate pre-schoolers with low and high working memory span (Espy & Bull, 2005). Similarly, children can employ different attentional strategies to be more successful in handling a gratification delay task (e.g. by redirecting attention to an object distinct from the object of desire; Białecka-Pikul, Byczewska-Konieczny, Kosno, Białek, & Stępień-Nycz, 2018). Also, it is suggested that set-shifting responses under tasks that require a motor response that is just emerging (e.g. descending a staircase), compared to tasks with low demands (e.g. walking on a flat ground), depletes attentional capacities for other aspects of the task (such as holding the set representation in mind) and children perseverate more (perseveration is a measure of CF; Berger, 2004). Hanania and Smith (2007) provided evidence for direct associations between cognitive flexibility and selective attention, by showing associations between performance on the Dimensional Change Card Sorting (DCCS) task (a task tapping CF) and a selective attention task on a cross-sectional study, and showing that training on the DCCS improved performance on the selective attention test through an intervention study. Differences in attention control have been shown to support performance on set-shifting tasks across the first years of life (e.g. Hanania & Smith, 2010; Kirkham, Cruess, & Diamond, 2003; Thelen, Schöner, Scheier, & Smith, 2001).

The development of attention and executive control processes (including EF), is generally agreed to be susceptible to environmental influences (Conejero & Rueda, 2017; Diamond & Ling, 2016; Fiske & Holmboe, 2019; Hendry et al., 2016; Posner et al., 2012; Rueda et al., 2005; Scerif, 2010) that may alter their developmental trajectory as an adaptive response (Johnson et al., 2015; Scerif, 2010; Wass & Scerif, 2012; Werchan & Amso, 2017).

1.1.5. Early environmental influences on attention and Executive Function

The slow maturation of the frontal cortex and its networks (Benes, 2001) suggests that it is heavily dependent on the environment for its development (Werchan & Amso, 2017), and that it is malleable and vulnerable to everyday activities (Diamond, 2013). There are characteristics of the child's environment that appear to contribute to better EF outcomes later in life (Banerjee, Middleton, & Faraone, 2007; Froehlich et al., 2011) and others that act as stressors or barriers to EF development. A very important and replicated factor thought to be related to EF is socioeconomic status (SES; Hackman, Gallop, Evans, & Farah, 2015; Howard et al., 2019). SES encompasses a wide range of potentially modifiable factors: parenting consistency and scaffolding, sleep (Bernier, Beauchamp, Bouvette-Turcot, Carlson, & Carrier, 2013), physical activity, access to quality education/child-care, and specific risk factors (e.g. substance abuse, violence); these, in turn, can mediate many other early life risks associations with EF.

Both attention control and EFs are subject to protective and promoting interventions during development (e.g. through computerized brain training; Owen et al., 2010; Rueda et al., 2005; Wass & Scerif, 2012; Wass, Porayska-Pomsta, & Johnson, 2011). The conditions deemed essential for executive development have been proposed to relate to constant challenge, in real-world achievable situations, and during a prolonged period (Diamond & Ling, 2016). Such a situation could be imposed by strict rule enforcement (e.g. by a social partner or a physical barrier) that displaces a child's impulses while providing them with the opportunity to achieve a goal.

Digital media activity (including watching entertainment television, household television exposure, and playing video-games) has been the focus of a multidisciplinary debate around potential impact (negative and positive) on attention control and executive function development (D. R. Anderson & Subrahmanyam, 2017; Bavelier et al., 2010; Christakis, 2016; Nikkelen et al., 2014; Rothbart & Posner, 2015). In the next few sections of this introductory chapter, I will contextualise the modern family media environment and describe the associations and potential pathways of influence by digital media on the developing mind.

1.2. The digital media environment during infancy and toddlerhood

Nowadays, digital media is ubiquitous in the family environment (from the bedroom to the car) and occupies an increasing role in young children's play and learning environment.

The modern digital media environment

When Apple launched the iPhone in 2007, and the iPad in 2010, they brought mobile touchscreen platforms to the mainstream and changed completely the figures around media use and consumption for this century. Only nine years after the advent of touchscreens, *Ofcom* (the UK communications authority) reported that 86% of UK families predominantly accessed the internet via touchscreen devices (smartphones and tablets) rather than traditional computers (Ofcom, 2016) showing that mobile media has become an integral part of family life. This is also reflected in changes in young children's media consumption, particularly because mobile interactive media brings more accessibility (age of first exposure has shifted), portability (both the amount per day has increased and the use has become more widespread across multiple contexts, i.e. at home, in the restaurant, while commuting), and entertainment potential for this age range.

A 2017 US large representative survey revealed that children under eight years-of-age spent 2h 19min /day with screen media, from which 48 minutes was spent on mobile screen media, i.e. a third of all screen time was mobile (Rideout, 2017). This average amount of time per day spent with mobile devices has increased exponentially from previous years – see Figure 1. 3; which is probably due to increased family ownership of these devices (in 2017 98% of families owned at least one mobile device) which increases children's accessibility to mobile screens (Rideout, 2017).

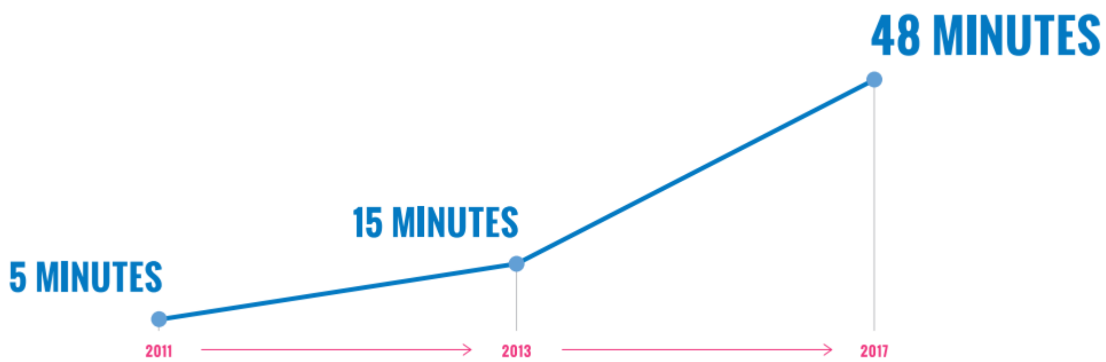

Figure 1. 3. Average amount of time spent on mobile devices per day among children 0 to 8 years old. Adapted from "The common sense census: Media use by kids age zero to eight" by V. Rideout, 2017, Common Sense Media.

These patterns are also seen in the UK. Pre-schoolers use of touchscreen devices increased rapidly in recent years, with mobile phone use in 3-4 year-olds increasing from 20% to 32% between 2013 and 2018, and tablet use increasing from 28% to 58% in the same period (Ofcom, 2019). Numbers from the TABLET (Toddler Attentional

Behaviours and LEarning with Touchscreens) project[1] survey, the first UK scientific study on the topic of 6- to 36-month-olds use of touchscreen devices (i.e. smartphones, tablets, and touchscreen laptops) and the project providing all the data in this thesis (see more details in Chapter 2), showed that daily touchscreen-device usage is seen as young as 6 months of age (Bedford et al., 2016). This survey also showed that usage statistics increase with age, with about 51% of infants between 6 to 11 months using a touchscreen daily (on average for 9 minutes a day); 73% of 12-18 months-old (for about 19 min/day); 81% of 19-25 months-old (25 minutes a day); and 92% of toddlers between 25- to 36-month-olds (nearly all sample, on average for 44 minutes a day). Further, parents reported that 10% of all children under three had their own touchscreen device (Bedford et al., 2016). These figures show that digital mobile touchscreen media has become more accessible, used by ever-younger children, and for a prolonged amount of time.

Television viewing is still the most prominent form of media use in young children (Huber, Highfield, & Kaufman, 2018a; Ofcom, 2019), but there is a general downward trend in television viewing **watched on a TV set** (Ofcom, 2019; Stewart, Duncan, Walker, Berry, & Schofield, 2019) such that television/ video content is being viewed on other devices, for example on interactive screen devices (Ofcom, 2019; Rideout, 2017). In 2018, nearly half of the UK children aged 3-4 reported having used YouTube, with only half of these children using YouTube Kids exclusively, and the most prevalent content (80% users) watched being cartoons/ animations/ mini-movies or songs (Ofcom, 2019). Indeed, digital content targeted towards children has also changed in the last decades. Overall, current US popular children's television shows are most often animated and fantastical (portraying physically impossible events and fantastical characters), containing little educational content (Taggart, Eisen, & Lillard, 2019). However, while 80% of 6- to 11-month-olds use touchscreens mostly to watch videos, more than half (57%) of toddlers above the age of 2 use these devices to actively scroll or tap the screen (Bedford et al., 2016). Indeed, children can navigate around touchscreen apps by age of 2 using swiping and tapping gestures (Ahearne, Dilworth, Rollings, Livingstone, & Murray, 2016; Cristia & Seidl, 2015; Hirsh-Pasek et al., 2015; Hourcade, Mascher, Wu, & Pantoja, 2015). It is thus clear that touchscreen media devices allow different types of use even for very young children, that range in terms of the interactivity, stimulation and developmental value they offer.

[1] *https://www.cinelabresearch.com/tablet-project*

Family screen time management also appeared to have changed with the introduction of modern media. Around touchscreen mobile devices, parental mediation of *screen time* seems to be primarily restrictive, reactive and focused on the functionality of the platform (Domoff et al., 2019). Parents seem to see mobile interactive screens as having a big potential for learning opportunities (Huber, Highfield, & Kaufman, 2018a), but are less confident in choosing and monitoring the touchscreen media content (e.g. to assess which interactive content is appropriate; Kostyrka-Allchorne, Cooper, & Simpson, 2017b), which creates anxiety and guilt around the topic (Toddlers & Touchscreens Team, 2019). Almost all new communication medium used by children has been viewed with both concern and hope by educators, development experts, and parents (Wartella & Robb, 2008). Similar concerns to the ones directed at touchscreen platforms (e.g. "More than two hours screen time a day could damage children's brain development", Telegraph; Donnelly, 2018) were previously seen directed at reading novels and comic books, radio, and movies; with time all these concerns dissipated (Carr, 2011). On the other hand, new media also brings expectation for potential benefits to learning and education; and, importantly, hope to narrow the SES-related gap, by means, for example, of national directives to broadcast educational television. This is particularly evident in the case of *Sesame Street*, a very popular program first broadcasted in the US in 1969, which had many favourable commentaries about positive effects on school-readiness skills and social-policy implications (e.g. D. R. Anderson & Hanson, 2010), but also had very charged responses about the show damaging children's brains, and creating a "drugged" (Moody, 1980) or "blank mind" (Singer, 1980) generation. These claims continue today, now targeted to new mediums such as smartphones and tablets.

Why are touchscreens a fundamentally different platform?

In the scientific community, touchscreen media have been generally seen as a more developmentally appropriate media platform, because it is, in contrast to television, contingent and interactive, enabling **manipulation** (physical exploration, multimodal stimulation), **scaffolding** (contingent feedback), and **control** (sense of agency, self-pace), like a traditional toy (Christakis, 2014; Geist, 2014; Zimmermann et al., 2017). However, there are other important considerations about this platform that make it fundamentally different from conventional media (Radesky, Schumacher, & Zuckerman, 2015a), and that may help us understand the potential associations with cognitive development.

- **Portability**: smartphones and tablets are mobile and wireless, which means that parents can take them everywhere, allowing them to be used in a wide variety of contexts, including places where screen media was previously uncommon (Lauricella, Blackwell, & Wartella, 2017), potentially displacing more "off-screen" activities. This portability also gives rise to the *pass-back phenomenon* where parents hand the devices to keep children occupied in a variety of occasions, usually for a relatively short interaction (Chiong & C, 2010; Wartella, Rideout, Lauricella, & Connell, 2013), and often to entertain or distract the child (e.g. on the bus, during meals in a restaurant).

- **Individual use**: these devices are small and often used at a close distance. This, and the family ownership of multiple screens (98% of families of children 6-36 months own multiple devices, with some owning as many as 14; Bedford et al., 2016), leads to regular parallel family media use (Domoff et al., 2019), with multiple family members engaged with their own mobile devices (young children using on their own) while simultaneously being exposed to background screen media (i.e. media multitasking). Media multitasking is another phenomena around modern digital media use whereby the simultaneous use across different platforms (i.e. concurrent multi-screen use) even for young children (e.g. watching television while playing on the tablet) is common. Children who prefer and use more touchscreen devices are more likely to use more than one screen device simultaneously (Kostyrka-Allchorne, Cooper, & Simpson, 2017b).
- **Choice of content**: a crucial aspect of these devices is the variety of content and activities they can provide. The introduction of interactive smart technologies also brought about the production and commercialization of a panoply of new digital content. For young children, this market includes e-books (interactive or not), YouTube, video-calls, games, digital craft apps (drawing, building), among others. While this variety has incredible educational and entertainment potential, the quality of content also varies hugely: free apps have more features that impede learning such as adverts and pop-ups; while curated educational and ad-free content is often paid for and less established (e.g. kids app Hopster; Ragoonanan, 2017); and contemporary parents have more difficilty monitoring content due to less familiarity with industry ratings for digital games and apps (Kostyrka-Allchorne, Cooper, & Simpson, 2017b).

Due to the rapid evolution of technological media, and the lag of published scientific evidence following it, many of the most pressing questions about the impact of today's media can only be informed by focusing on the impact of yesterday's media. Conventional screen media comes in two broad forms: television and interactive screen media (computer or console video-games). All screen media (including touchscreen media) share similar audio and visual technology, representations, and formal features (like cuts, rapid changes, zooms), and differ in terms of the requirement of some form of response and choice by the user (interactivity), which in turn determines the progress of the content over time.

Until the introduction of touchscreen-like frameworks, the distinction in terms of interactivity was very evident (watching television is observational, video-games require some form of motor action). But for touchscreen devices the distinction is less clear, as both functionalities (passive or interactive use) can happen in the platform. Importantly, both passive and interactive use **on a touchscreen device** do not necessarily provide the same experience than passive or active use on a conventional platform: for example, when watching videos on YouTube on an iPad, even a young child can at any time pause, resume, repeat, move to a new video, or let the app drive the next content (auto-play), allowing both passivity (as on a television) and a sense of agency and choice for what is being watched (as on a video-game); correspondingly, while touchscreen apps and games are broadly interactive (similarly to a joystick on a game console), the applications are designed to have highly salient and rewarding features ("nudge" design; Carr, 2011), are usually not very dynamic and demanding (due to poorer graphics and memory systems of mobile devices), and are constantly disrupted by advertisement, which questions the comparison with video-games.

Nevertheless, given the lack of rigorous empirical evidence as background for studying the impact of modern touchscreen mobile devices on attention and executive function, one needs to draw on evidence from conventional media. Research to date has extensively examined television and video-gaming impact on development in a variety of domains (e.g. sleep, language, behavioural problems). Given that the focus of this thesis is on attention and executive function development, the below literature review will describe the research studies and pieces that investigated the associations with these abilities, splitting in terms of television and video-gaming.

1.3. Television and children's attention and Executive Function

1.3.1. Evidence for the associations with television exposure

The extent to which attention and executive function processes are affected by televised media has been researched extensively using different methodologies, including correlational (cross-sectional and/or longitudinal), and experimental studies. While some studies have focused on time/quantity spent viewing television (e.g. Christakis et al., 2004), others have investigated the quality (e.g. Barr, Lauricella, Zack, & Calvert, 2010; Geist & Gibson, 2000) or editing pace (e.g. Lillard & Peterson, 2011) of the content viewed, or the age of exposure to television (developmental susceptibility; Barr et al., 2010; S. Cheng et al., 2010).

Correlational studies of television viewing

In correlational studies, viewing time, drawn from parent-report questionnaires or media diaries, is typically the main predictor variable (Kostyrka-Allchorne, Cooper, & Simpson, 2017a). In general, this line of research shows small but significant short and long-term associations between excessive television viewing and attention (Nikkelen et al., 2014) and EF difficulties (Kostyrka-Allchorne, Cooper, & Simpson, 2017a).

Cross-sectional studies have shown that concurrent television daily viewing time is associated with parent (Ebenegger et al., 2012) and teacher (C. J. Miller et al., 2007) reports of ADHD-like behaviours (attention difficulties), and direct measures of motor activity (an index of hyperactivity; C. J. Miller et al., 2007) in young children (up to 6 year-olds); and throughout development (5-17 year-olds; Lingineni et al., 2012; van Egmond-Fröhlich, Weghuber, & de Zwaan, 2012). Although cross-sectional studies show a negative association between television viewing and attention outcomes, even when co-varying for age, gender and SES (C. J. Miller et al., 2007), they do not allow scientific conclusions about developmental trajectories.

Longitudinal designs, on the other hand, provide a temporal order of associations that can inform the developmental dynamics involved. A substantial amount of research in the field has used large, representative, population-based samples (e.g. national survey data) and longitudinal designs, which provide observation of the temporal sequence between variables, thus enabling some plausible inferences about cause and effect. One of the most influential, but scrutinized[2], study was reported by Christakis and his colleagues (2004). In a large US survey dataset, they showed a positive association between total time viewing television both at 1 and 3 years with attention problems at 7 years (indexed by a hyperactivity scale of behavioural problems), controlling for various confounding variables. Subsequently, others have replicated this finding by showing a positive association between television viewing at 18 months, but not concurrent viewing, and attention problems one year later in a Japanese sample, controlling for child and

[2] *The study was subsequently reanalysed by independent researchers, who questioned the robustness of findings. Foster and Watkins (2010) analysis did not support the original report's interpretation, by showing that the association found was only significant for excessive amounts of TV viewing (i.e., between 6 and 7h of television a day), and by failing to replicate the relationship when controlling for additional covariates (i.e. maternal achievement and family poverty status).*

family characteristics (S. Cheng et al., 2010); and further demonstrated that the associations of childhood (i.e., ages 5–11) amount of television viewing and attention problems extends into adolescence, after controlling for early attention, cognitive ability, and SES (Landhuis, Poulton, Welch, & Hancox, 2007). Although other studies failed partially to replicate these findings (Stevens & Mulsow, 2006), particularly in older children (Parkes, Sweeting, Wight, & Henderson, 2013; Schmiedeler, Niklas, & Schneider, 2014), a meta-analysis from Nikkelen and colleagues (2014) demonstrated a modest but significant association between television viewing and ADHD-like behaviours that cannot be accounted for by known confounds such as SES.

Zimmerman and Christakis (2007) further investigated the associations found in the 2004 study by examining possible moderations by age and content of television viewing. They showed that viewing of entertainment programs (both violent and non-violent, e.g. *Looney Tunes* and *Flintstones*) before the age of 3 years predicted attention problems 5 years later, while no associations with viewing educational television (e.g. *Sesame Street*) were found. Also, television viewing at the age of 4 to 5 years (even entertainment content) was not associated with attention problems 5 years later, highlighting the sensitivity period for television exposure in the early years (< 3 years-old). Similarly, viewing time of content rated inappropriate for young children, but not overall viewing time, was found to be associated with teacher-reported classroom hyperactivity in a low SES sample (Conners-Burrow, McKelvey, & Fussell, 2011). This might be related to another finding in the field provided by Martin and colleagues (2012): they showed that household background TV at 2 years was associated with poorer attention outcomes at 5 years, while other measures of household chaos were not associated with the outcome. It seems that factors such as type of content (educational or entertainment), age of onset (infancy versus school age), and background household exposure, are crucial in the pathway of long-term influence of television on children's attention and ADHD-related behaviours (S. Cheng et al., 2010; Martin, Razza, & Brooks-Gunn, 2012; Zimmerman & Christakis, 2007).

ADHD diagnostic symptoms (difficulties with attention control, along with hyperactive and impulsive behaviours, American Psychiatric Association, 2013) often co-occur with EF deficits (Barkley, 1997; Johnson, 2012). When direct measurements of EF are included in research designs, the evidence also suggests a consistent negative association between television viewing before the age of 3 and poorer outcomes (Kostyrka-Allchorne, Cooper, & Simpson, 2017a; Lillard, Li, & Boguszewski, 2015b), although aspects about the context of the television viewing and characteristics of the child and family environment are important (Kostyrka-Allchorne, Cooper, & Simpson, 2017a; Linebarger, Barr, Lapierre, & Piotrowski, 2014).

For example, Linebarger and colleagues (2014) have showed a complex pattern of associations between child cumulative risk (i.e. age, and family susceptibilities, including parent responsiveness, educational and economical background), media exposure content (entertainment or educational) and context (background or foreground TV), with parent-reported EF during early childhood. Using a study with a Chinese sample, Lillard and colleagues (2015) have reported a negative association between parent-reported EF and television viewing time; and took into consideration in their conclusions the fact that the great majority of viewing time is spent on entertainment, as educational television is rare in China.

In contrast to parent- or teacher-reported measures, a few studies have used performance-based measures of either attention or EF, broadly replicating the previous findings with more rigorous research methods. Zimmerman and Christakis (2005) reported, using a large population-based sample, a modest adverse association between television viewing before the age of 3 years and WM at the age of 6. Nathanson and colleagues tested 4-year-olds on a battery of EF tasks, including measures of cool-IC and WM, which they used to create a composite score. While their findings suggested that effects may vary with content type, both early television viewing (retrospective onset age of television viewing) and cumulative time viewing television (both on the foreground and background) were negatively associated with EF performance (Nathanson, Aladé, Sharp, Rasmussen, & Christy, 2014). Barr and colleagues used a similar approach to investigate executive function in pre-school years, adding a longitudinal design to investigate the temporal order of effects. They investigated whether television viewing at 12 months or at 3 years later predicted EF outcomes. They showed that viewing of adult-directed content and background TV in the house were associated with poorer EF; with the amount of adult-directed television watched in infancy and concurrent total household television associated with lower parent-report EF, and high exposure to adult-directed content concurrently associated with poorer EF cognitive measures (lab-measure of IC and CF). However, the child's support environment might have an important role, given that other studies have showed that parental scaffolding at 3 years was a stronger predictor of EF abilities (IC and WM) at 5 years than television viewing (Blankson, OBrien, Leerkes, Calkins, & Marcovitch, 2015).

Overall, it seems that attention and EF negative outcomes are associated with television viewing, particularly with entertainment and adult-directed programming, but it is important to note that the evidence presented here is purely correlational. Correlations, including longitudinal correlations, are insufficient demonstrations of causality, since the observed relationships may be mediated by third factors that were not measured (e.g. genetic predispositions).

Experimental studies of television

Cross-sectional and longitudinal studies are a suitable alternative to controlled experiments, particularly when experiments are borderline unethical – such as the case of exposing little infants to absurdly high levels of television, *a la* Christakis and Ramirez stress-inducing protocol in mice pups (Christakis, Ramirez, & Ramirez, 2012). For that reason, most of the research on media use is drawn from naturalistic observation of media behaviours and outcomes. There are, however, some experimental studies that worked around this ethical issue, by using small doses and manipulating content or context of viewing.

These controlled experiments are crucial to further our understanding of how television may affect children's cognition. The studies can be divided based on the theoretical pathway of influence they were aiming to examine, either investigating how programming content (particularly pacing or novelty rates) influences executive function and attention in the short-term, or by studying how background television affects attention during play, including joint-attention with parents.

A small number of research groups have focused on examining the immediate effects of television viewing on attention and executive function in preschool, by comparing differing types of content typically to a non-screen-based control condition. In one experiment (D. R. Anderson, Levin, & Lorch, 1977), a group of 4-year-olds watched a fast-paced episode of *Sesame Street* (more frequent shot changes and faster character movement), a second group was shown a slow-paced *Sesame Street* episode, and a third group had stories read to them by a parent. After the 40-minutes intervention, children did the Matching Familiar Figures Test (a measure of IC), a jigsaw puzzle, and a 10-minutes free-play period. No differences were observed in IC or sustained attention to the puzzle or the toys, and the authors concluded no immediate effects of television (fast- or slow-paced) on attention-related behaviours. However, a later study with school-age children (Gadberry, 1980), used the same impulsivity measure to assess the effects of a 6-weeks No-TV intervention. The children whose families restricted television viewing significantly reduced television viewing time, increased reading time in the home, and had longer latencies and more correct responses in the impulsivity test (indicating more reflectivity/ less impulsivity). Importantly, all television viewing measures were reduced in the intervention group, compared to the control, except for educational TV programs viewing (which included *Sesame Street*). Besides, latencies on the impulsivity task were negatively correlated with times viewing inappropriate content (aggressive and commercial programs) but positively correlated with the viewing of educational programs. It is important to highlight that both studies were conducted in the early years of development and broadcasting of child-directed educational content, and that *Sesame Street* is generally considered a slow-pace show (in comparison with more recent cartoons and programs, which have become more fast-paced, violent, and arousing; Bushman, Jamieson, Weitz, & Romer, 2013; Koolstra, van Zanten, Lucassen, & Ishaak, 2004).

Another more recent experimental study found evidence for a detriment on attention performance following watching a fast-paced entertainment modern program (Geist & Gibson, 2000). In this study, 4- to 5- year-old children were asked to watch either a slow-paced educational show (*Mister Rogers Neighbourhood*), or a fast-paced action entertainment show (*Mighty Morphin' Power Rangers*), or to take part in educational activities. During a 30-min play session done post-viewing, children who watched the fast-paced entertainment show switched more frequently between activities (suggesting more distractible behaviour) and spent less time on each activity (less sustained attention), than children in the slow-paced and the control group. To dissociate the editing pace (slow vs fast) from content type (educational vs entertainment) effects on different networks of attention, Cooper and colleagues (2009) carried out an experiment with 4- to 7-year-olds, using their own experimental films which manipulated pace (number of edits), without compromising content, and used a child adaptation of the Attention Networks Test (a flanker-type continuous performance task; Rueda et al., 2004a). They found an interaction effect between age and condition (slow, fast) on the orienting scores (a higher score is assumed to reflect a more competent orienting network and a more efficient voluntary shift of attention to the spatial cue), in a way that younger children who watched a slow-paced film had higher orienting scores, but the effect was reversed for the older kids. They also found a trend (p = 0.08) for larger alerting scores for 4-year-olds in the fast-paced group; and that children aged four and six in this group, but not the children aged five in this group, had shorter reaction times (the latter finding being reported in a paper by the same author in 2017; Kostyrka-Allchorne, Cooper, Gossmann, Barber, & Simpson, 2017c). They also reported a main effect of pace in overall accuracies, such that children who watched the fast-paced film were more accurate. Given the small sample and the preliminary nature of the study (this was the first and only study using a classic task of attention to dissociate performance), the authors did not go very far in interpreting their results besides arguing for some limited positive effects of watching a fast-pace program (Cooper, Uller, Pettifer, & Stolc, 2009). However, perhaps the effects found can be seen as an effect of fast-paced films on triggering alerting/vigilant behaviour, which in turn create optimal conditions for accurate performance on the task, while displacing resources for top-down shifts of attention (indexed by the orienting scores).

A set of experiments done subsequently by Lillard and colleagues helped advance the content/pace debate substantially. In their first experiment, 4-year-old children watched for 9 minutes either a rapidly paced entertainment cartoon (*Sponge Bob SquarePants*), a slower paced educational program (*Caillou*), or were asked to spend 9 minutes drawing. Following the experimental procedure, the children were given a battery of four tests of executive function. While the three groups matched in attention problems at the onset (on a 5-item parent-report measure of strengths and difficulties related to attention), the group that watched the entertainment fast-pace cartoon performed at a lower EF level (indexed by a composite score with three tasks, including measures of problem-solving, cool-IC, and WM) and had a shorter delay of gratification (hot-IC) than the other two groups. While the authors interpreted the effect as showing that children's executive resources were sensitive to the pacing of television (Lillard & Peterson, 2011), the programs also differed in the appropriateness of content (educational or entertainment). Moreover, since there was no pre-measurement of EF, it was not clear if the rapidly paced entertainment cartoon depleted EF or if the educational TV program and the drawing actually increased EF. Lillard and colleagues followed-up on these findings, and carried out three experimental studies to dissociate content pacing and type effects on EF of 4- to 6-year-olds. In a similar fashion to the previous experiment, two experiments showed consistently poorer EF performance (indexed again by a composite including WM, cool-IC, and also CF) related to the viewing of fast and fantastical, i.e. physically impossible events, content (even if defined as educational). However, in a final crucial experiment, researchers used again TV shows that differed in both the content (realistic vs fantastical) and the pace (fast vs slow), and showed a main effect on EF (composite including WM and cool-IC) specific to content (Lillard, Drell, Richey, Boguszewski, & Smith, 2015a). In this later experiment, both parent-reported and lab-measures of pre-EF were included in the design, strengthening the results. These results led the authors to hypothesise that processing fantastical content drained children's cognitive resources which, consequently, would lead to short-term executive function difficulties. The hypothesis that fantastical content excessively consumes executive resources, resulting in insufficient resources for subsequent performance, is supported by later studies showing increased brain activity in the left dorsolateral prefrontal cortex (area found to be active during EF performance, including WM, CF, and IC) right after children watched fantastical videos (Li, Subrahmanyam, Bai, Xie, & Liu, 2018). However, an important limitation of Lillard's studies was that the films used in their studies were not custom-made (they were all commercially available cartoons or programs), and so also varied in other aspects of content and audio-visual characteristics.

More recently, a set of experiments by Kostyrka-Allchorne and colleagues attempted to dismiss the confounds that result from using commercially available shows, by producing their own clips that matched in audio-visual features and could isolate pace and content realism properties. In their first study, where pairs of children (2- to 5-year-olds) viewed together either a fast-pace or a slow-pace clip and were recorded pre and post-film during free-play, the group showed that pre-schoolers dyads shifted attention between toys more often after viewing a fast-paced clip, compared with dyads that viewed a slow-paced clip (Kostyrka-Allchorne, Cooper, Gossmann, Barber, & Simpson, 2017c), in line with another study reported above (Geist & Gibson, 2000). In a subsequent experiment, a between-subjects analysis of pace (fast, slow) was used to test 7-year-old children's performance on a cool-IC test (Go/No-go task). Immediately after the experimental procedure, in the first half of the task, children who watched the fast-pace video made more commission errors (no-go errors, a measure of failure to inhibit a response) than those who watched a slow-pace version, and showed atypical neural responses related to inhibition, supporting a prediction of a negative very short-term impact of fast pace videos on EF processes (Kostyrka-Allchorne, Cooper, Kennett, Nestler, & Simpson, 2019b). In a final experimental study, the authors followed-up on Lillard's 2 (pace: fast or slow) by 2 (realism: realistic or unrealistic) design to investigate independent effects of pace and realism (i.e. opposite to fantastical) on attention and IC, again using custom-made videos. The study found that children (3.5- to 5-year-olds) who watched the fast-paced video featuring a realistic story had faster reaction times on a continuous performance task (a task tapping into sustained attention, vigilance, and attention inhibition) compared to children who watched a slow-paced realistic version. They did not find any effects of either pace or realism in either omission (sustained attention) or commission (inhibition) errors in the task; but they found that children who had watched the unrealistic videos performed better on the day-night task (another measure of IC) than their peers who had watched videos featuring realistic content. In contrast to Lillard’s findings, in Kostyrka-Allchorne's studies it seems that pace was more detrimental to children's EF and that fantastical/irrealistic content attenuated the effects of fast pacing. In addition, the finding of faster reaction times after the fast-paced realistic video seems to be indicative of higher alertness and preparedness for quick action elicited by fast and visually salient changing stimuli on the film (Kostyrka-Allchorne, Cooper, & Simpson, 2019a).

All together, these studies seem to suggest that some features that are predominant in modern entertainment digital media (i.e. pace and novelty) result in more distractible behaviour during play and less voluntary/ goal-directed responding on direct laboratory tests of attention and EF, after children engage in television viewing. However, it is unclear whether cumulative exposure to these immediate effects leads to longer-lasting change in children's cognition and behaviour.

Another body of experimental research has suggested a potential impact of television as a secondary activity (in the background) to infants’ attention. These studies have shown that the presence of background television (child or adult-directed) may have a distracting effect on infants’ and toddlers’ attention to toys (Courage, Murphy, Goulding, & Setliff, 2010; Schmidt et al., 2008), and it may reduce the quality and duration of parent-child joint attention episodes (Courage et al., 2010; Kirkorian, Pempek, Murphy, Schmidt, & Anderson, 2009), by eliciting frequent shifts of visual attention between the toys and the screen(Setliff & Courage, 2011). In the long-term, these may be harmful to children’s EF development, given that reduced sustained attention, joint attention, and parental scaffolding may be detrimental for children's development of EF (Hammond, Müller, Carpendale, Bibok, & Liebermann-Finestone, 2012; Hendry et al., 2016). Moreover, these results support the correlational findings of negative effects of background television in the context of household chaos presented previously (i.e. Martin et al., 2012).

In conclusion, the evidence from the television literature generally points to negative associations between television viewing and children’s attention and EF development (Kostyrka-Allchorne, Cooper, & Simpson, 2017a; Nikkelen et al., 2014). Studies that measured television viewing in infancy (both with and without content analysis) have consistently shown that high levels of television viewing is associated with negative developmental outcomes for attention (S. Cheng et al., 2010; Christakis et al., 2004; Martin et al., 2012; Zimmerman & Christakis, 2007), and EFs (Barr et al., 2010; Nathanson et al., 2014; Zimmerman & Christakis, 2005), but also highlighted potential interacting factors to explain such associations, such as individual and family context, and content and editing features. Although these studies have not demonstrated a causal association of television viewing, authors have hypothezised the underlying mechanisms, or pathways of influence, from television exposure to cognitive outcomes.

The aim of this thesis was not to demonstrate causal associations but to test for associations with touchscreem media use in parallel with hypothesised underlying mechanisms, as a first step towards testing a causal relationship. In the next section, I will briefly describe the different pathways proposed by television researchers, which I believe are important to understand and discuss the results presented in later chapters. These concern direct and indirect pathways by which media can affect children executive systems, and are likely not mutually exclusive. The direct pathways are based on the content viewed and its formal features (e.g. fast-pace), or on the context of that exposure (e.g. background vs foreground television). The indirect pathways are not attributable to media *per se*, but to a direct influence on another variable (e.g. time on-screen displaces social interaction with caregiver or physical activity).

1.3.2. Direct pathways of influence

Passivity of the medium

The primary argument by early critics of television (in the 1970s and 1980s) was that television viewing is cognitively and physically passive, irrespective of the content watched (being violent, fast-paced, or educational). The consequences of watching television were seen as suppressing cognitive reflection (because actions and events on television are explicit, there is little room for inferential activities), memory encoding, planning, connected comprehension of discourse, imagination, and inference (Moody, 1980).

Viewing television is characterised by attention inertia, meaning that, the longer the attention to the screen is sustained, the more both selective attention to the screen and inhibition of stimuli around the screen area increase (i.e. the longer a look at the TV set has already been in progress, the less likely it is to terminate; D. R. Anderson, Alwitt, Lorch, & Levin, 1979; D. R. Anderson, Choi, & Lorch, 1987; Richards & Cronise, 2000; Richards & Gibson, 1997). Although this process aids information processing and encoding (at least in adults; Burns & Anderson, 1993), comprehensibility of the content does not seem to be a requirement for attentional inertia to television (Lorch & Anderson, 1979). Furthermore, children under 3 do not learn or transfer learning from a video compared with a real-life experience (Barr, 2010; 2013), usually referred to the video *transfer deficit* effect (D. R. Anderson & Pempek, 2005). The combining evidence that children fail to transfer from video, to discriminate comprehensible from incomprehensible videos before 18-24 months (Pempek et al., 2010), and to drive eye-movements in a goal-driven manner to comprehensible content before 4 years (Kirkorian & Anderson, 2017; 2018; Kirkorian, Anderson, & Keen, 2012), supports the view that infants and toddlers do not comprehend television content, even if they can attend to it for increasingly long periods of time. This implies that, while attention is elicited and sustained during television viewing (likely because of exogenously-driven orienting responses captured by saliency), content on videos is very difficult for younger audiences to understand, and so, potential learning benefits and opportunities are unlikely to arise from it.

Modern digital content: trigger of orienting responses

Attention to television seems to be episodic and selective. When the TV is on, children may exit and re-enter the viewing area multiple times during a program; in the moments they are in the viewing area they may attend towards and away from the screen repeatedly; while they are attending, they may scan different portions of the screen with greater and lesser intensity (D. R. Anderson et al., 1987; D. R. Anderson & Kirkorian, 2015). Digital scenes predominantly have perceptually salient features (rapid pacing/action, abrupt changes, sound effects, sharp edges and contrast; Itti & Koch, 2000; and movement; Mital, Smith, Hill, & Henderson, 2010) that elicit and maintain attention, i.e. looking, through orienting responses. These orienting responses can be triggered by televised scenes as early as 6 months of age (Gola, Kirkorian, Perez, Anderson, & Calvert, 2011), but only between 18 months and 5 years of age children start becoming sensitive to the linguistic and sequential comprehensibility of videos and increasingly integrate successive shots to create a representation of the narrative sequence (D. R. Anderson, Lorch, Field, & Sanders, 1981; Kirkorian & Anderson, 2018; Pempek et al., 2010; Richards & Cronise, 2000). With experience, children also come to learn that other formal television features (non-salient ones e.g. narration, or elements of the content that recur across episodes of a series; Crawley, Anderson, Wilder, Williams, & Santomero, 1999) are associated with comprehensible and entertaining (rewarding) content, and systematically direct their attention to them (D. R. Anderson & Lorch, 1983).

Audio-visual screen content is generally designed to guide attention towards reward (T. J. Smith, 2012). Young children’s contemporary television programs, even the ones claiming to be educational, predominantly rely on audio-visual saliency to capture attention (Goodrich, Pempek, & Calvert, 2009; Wass & Smith, 2015) and guide them to informative content (Franchak et al., 2016; Kirkorian et al., 2012). This implies that bottom-up attention is constantly elicited and attention consequently grabbed during these shows (Chun, Golomb, & Turk-Browne, 2011; Wright et al., 1984), and indeed, entertainment shows (which typically make more use of attention-grabbing audio-visual features, loud and salient events, and unexpected events) seem to elicit attention shifts more frequently (more fixations per minute) than educational ones (Lillard, Li, & Boguszewski, 2015b).

This constant and systematic triggering of attention in a bottom-up fashion by TV shows has been a common negative aspect used by researchers to argue for a causal impact from television viewing on attention/EF development. This influence by saliency and novelty on screen might be seen related to different, but not mutually exclusive, hypotheses: reliance on exogenous cues, consequent displacement of top-down development, and overloading of executive resources.

Firslty, bottom-up orienting is seen as an involuntary, reflexive form of attention, distinct from top-down attention control required in many “real-life” situations. These exogenous cues capture children’s (and adults’) attention to the screen and also maintain their, otherwise distractible, attention there, providing a continual external support to attention. As a consequence, extended exposure might lead to habitual reliance on the environment to sustain attention, or habitual favouring of bottom-up processes in everyday situations (like in a classroom; Christakis, 2009; Lillard & Peterson, 2011; Shin, 2004; Zimmerman & Christakis, 2007). The exact long-term mechanism has not been specified, but it is not unreasonable to consider that neuroplasticity mechanisms could strengthen neural networks that support such bottom-up attention through experience.

In addition, it is thought that as a consequence of this habitual engagement of bottom-up attention, somehow the development of top-down attention is disrupted (e.g. Christakis et al., 2004; Singer, 1980; Zimmerman & Christakis, 2007). This could be viewed as a balance between processes (i.e. if more bottom-up, less top-down), or that children could be displacing opportunities to “exercise” and challenge their top-down attention control (e.g. Baumeister, Vohs, & Tice, 2007) because the automatic attention reactions happen without the requirement of active cognition (Singer, 1980; Singer & Singer, 1983), or internal drives to generate attention.

A related hypothesis is advocated by Lillard and colleagues (Lillard & Peterson, 2011). In their view, the flow of fast (too much information or too rapidly for children to process it) and/or fantastical (i.e. events that violate expectations which are difficult and require more resources to process them) events is beyond the young brain's cognitive capacities. While attention is effectively sustained to the screen (in a bottom-up fashion) by these events, the demanding flow of surprising events overloads attention resources, leading to a short-term depletion/shut-down of resources needed for executive performance, which extends after viewing has stopped. While there is some evidence that viewing fantastical events activates brain executive networks resulting in disruption of performance straight after (Li et al., 2018), it is not clear from this hypothesis how the short-term exhaustion of executive resources impacts in the long-term the development of EF or attention control.

Media experience as stress-inducing/ overstimulating

A very popular argument from television experts is the notion that television "overstimulates" the developing brain with "excessive non-normative stimulation" (Christakis et al., 2012, p. 1). Some researchers propose that this overstimulation (consisting of the presentation of a constant and fast flow of interesting and rewarding events) conditions children to always expect high levels of input and stimulation (relative to the real-world) leading to shorter attention spans in relatively less stimulating activities later in development and impaired learning (Christakis, 2016; Christakis et al., 2012; Gentile, Swing, Lim, & Khoo, 2012; Shin, 2004). This shift in expectations for stimulation could arise potentially from an increase in arousal while viewing television, negatively affecting children's baseline arousal levels (Huizinga, Nikkelen, & Valkenburg, 2013).

Another related hypothesis is that overstimulation from digital content creates an acute stress episode. Certain media content (especially those with emotionally disturbing contents, within either television or video games; Maass, Lohaus, & Wolf, 2010) induce physiological arousal, i.e. elevated heart rate (Ravaja, Saari, Salminen, Laarni, & Kallinen, 2006), noradrenaline (Goldstein, Eisenhofer, Sax, Keiser, & Kopin, 1987), and cortisol levels (Hébert, Béland, Dionne-Fournelle, Crête, & Lupien, 2005), that resemble a mild stress response. High levels of arousal induced by these episodes lead to quick but unselective responses (increased distractibility) that ultimately impair effective information processing and cognitive performance (Aston-Jones & Cohen, 2005; Maass, Klöpper, Michel, & Lohaus, 2011), and are linked to immediate and prolonged impairments of prefrontal functions (i.e. executive control; Arnsten, 2009; Diamond, 2013), potentially by altering its networks' neurochemical environment (e.g. with excess of dopamine; Cerqueira, Mailliet, Almeida, Jay, & Sousa, 2007).

Modern digital content: rewarding pathways

Technology use can stimulate physiological arousal and the secretion of dopamine to cortical regions of the brain that are sensitive to reward and reinforcement, particularly when playing games (Bavelier, Green, Pouget, & Schrater, 2012). Fronto-striatal pathways (implicated in disruptions to the arousal-regulation systems) have also been shown to be activated by certain media activities, in particular, video games (Bavelier et al., 2010; Hoeft, Watson, Kesler, Bettinger, & Reiss, 2008; Koepp et al., 1998; Matsuda & Hiraki, 2006). Little is known about how these pathways mature or develop in relation to media. However, it is plausible that media might hinder the development of internal mechanisms of regulation (i.e. not supported by constant rewards), and promote risk-taking (Christakis et al., 2012), reward-seeking, and immediacy oriented behavior (Wilmer et al., 2017).

Media in the background

It has been hypothesized that television, when used as a secondary activity (i.e. turned on in the background), is distracting and disruptive to the primary activity in which the child (or the parent) is engaging (e.g. play or joint-play; e.g., Courage et al., 2010). This is because it acts as a distracter (through incidental sounds and salient visuals) that attracts bottom-up attention and directly disrupts sustained attention to and capacity available for primary task performance. Long-term exposure to background television could negatively influence cognitive development, by displacing moments of sustained attention important for development of executive attention (Barr et al., 2010; Kirkorian et al., 2009; Radesky et al., 2015b; Schmidt et al., 2008; Setliff & Courage, 2011), or indirectly disrupting executive processes, by decreasing active engagement and scaffolding from parents, which is important for EF development (Hammond et al., 2012).

1.3.3. Indirect pathways of influence

Digital time-displacement

One of the earliest hypotheses about media impact, but still very relevant, concerns time displacement. The underlying assumption is that if children are watching television (or any other media platform), they must be doing less of something else (e.g. D. R. Anderson, Huston, Schmitt, Linebarger, & Wright, 2001; Shin, 2004; Wiecha, Sobol, Peterson, & Gortmaker, 2001; Zimmerman & Christakis, 2007). Time spent viewing television or playing video games might displace time that would have otherwise been spent on activities that promote the development of executive control. To the extent that digital media use does not tax executive control resources, time spent with such media may weaken ones' ability to exert them (Baumeister et al., 2007), but also displace other factors important for the development of executive processes such as social interaction with parents (Bernier et al., 2012; Kirkorian et al., 2009), sleep (Bernier et al., 2013; Cheung, Bedford, Saez De Urabain, Karmiloff-Smith, & Smith, 2017; Mireku et al., 2019; Thompson & Christakis, 2005), physical activity (Carson & Kuzik, 2017; Diamond, 2013), and bodily sensorimotor interactions with the environment (Thelen et al., 2001).

However, time displacement could potentially lead to a positive or negative influence from digital media on development depending on the activities it displaces, i.e. if it displaces valuable developmental activities, or if, on the other hand, it displaces activities such as being with an unresponsive caregiver and/or in a low quality learning environment. In these contexts, spending time with touchscreen media devices could have benefits for EF, given the market of varied content it provides, including developmentlly appropriate games and applications designed to promote active, relevant, and socially interactive learning (Hirsh-Pasek et al., 2015) and may “train” executive abilities (Diamond & Lee, 2011; Diamond & Ling, 2016; Rueda et al., 2005).

Child and family susceptibility (media attraction)

Generally, the associations between executive performance and habitual media use presented above are found in cross-sectional or longitudinal studies, and so are not a demonstration of causality. It is, therefore, equally possible that 1) media use “causes” differential performance, 2) that individual traits “cause” more or less media engagement, or that 3) this relationship is bidirectional. In that sense, pre-existing factors (e.g. specific attentional traits, or genetic variability related to levels of neurotransmitters implicated in attention network systems) may affect the degree to which children engage in media use (Radesky, Silverstein, Zuckerman, & Christakis, 2014) and favour content congruent with their profile (Valkenburg & Peter, 2013). Because children are more engaged and allocate more resources while processing congruent media content, familiarity and pleasure during the activity are strengthened, which can lead to more exposure and render them more susceptible to media effects (Valkenburg & Peter, 2013).

Indeed, children with early attention difficulties or poor self-regulation seem to favour television to a greater extent (amount of use) than children without attention problems (Acevedo-Polakovich, Lorch, Milich, & Ashby, 2006; Barkley, 2004; Radesky et al., 2014). Children with poor working memory capacity also seem to have more difficulties learning from a video (Choi, Kirkorian, & Pempek, 2018), which can make them more vulnerable to the effects that arise from lack of comprehension of television programs. Thus, child dispositions simultaneously predict children's media use and enhance media effects.

Studies on neurodevelopment disorders of attention are also consistent with this hypothesis, with ADHD being associated with overuse (and severity specifically correlated with the amount of use; Barkley, 2004), and also with unusual sensitivity to screen media technology effects (Engelhard & Kollins, 2019).

Third variable hypothesis

Media studies, and particularly correlational ones that use quasi-experimental designs based on observations of media habits, are very susceptible to the third variable effect or spurious association problem. Although most of the findings described below account for a wide range of variables as covariates, digital screen time can potentially be a proxy of, or effects confounded by, many sorts of maladaptive family behaviours (e.g. less parental supervision, chaotic house enviroment; Martin et al., 2012) that negatively relate to child development; or, in contrast, index more access to educational resources and opportunities (because digital media devices are expensive).

While this summary of the literature regarding associations between television viewing and attention and EF outcomes, and the different mechanistic pahtways that have been proposed to explain such associations, clearly points to detrimental effects of television, it is worth acknowledging that beyond infancy (> 2 years) watching developmentally appropriate and educational programs may have the capacity to enhance children's school readiness, basic literacy and numeracy (e.g. D. R. Anderson & Hanson, 2010; Baydar, Kağitçibaşi, Küntay, & Gökşen, 2008; Linebarger & Walker, 2005; Schmidt & Anderson, 2009; Zill, Davies, & Daly, 1994), and also relates to positive academic outcomes (D. R. Anderson et al., 2001; Rice, Huston, Truglio, & Wright, 1990; Wright et al., 2001). Digital media products have the potential to increase children's access to information and education (Mielke, 1994; Wright & Huston, 1983), improve learning opportunities, and narrow the SES-related achievement gap. Thus, policy-makers should encourage the entertainment industry to work with educators/ developmental researchers (Bavelier et al., 2010; Dore et al., 2018; Mayo, 2009) to create (research and develop) **free** quality content for all the younger generations.

Although touchscreen mobile devices might be a developmentally more appropriate platform for infants and toddlers than television (Christakis, 2014; Geist, 2014;

Zimmermann et al., 2017), a lot of the time a young child is using a touchscreen medium they are doing so to watch videos (see Kabali et al., 2015; and Figure 2. 2 in the Chapter 2 of this thesis). It is important to note that, in this case, while the content is similar, the medium is not, and the question of whether similar effects on attention and EF from television viewing are seen in relation to content streamed on a touchscreen device has not been answered. However, a few studies have supported the hypothesis that the interactivity of a touchscreen medium improves toddlers' learning from screens (Huber et al., 2016; Kirkorian, 2018; Kirkorian, Choi, & Pempek, 2016), suggesting that the experience of watching videos on a touchscreen might not be equivalent to watching videos on television.

In regards to the current thesis, I argue that, on a touchscreen, content features (salient and rewarding content) might parallel the television ones, while other interface features (self-control of pace, sense of agency, frequent prompting of bodily actions, handheld physical experience) can provide an experience somewhat similar to video-gaming, thus potentially producing effects that are a hybrid of television and videogames.

1.4. The case of action video-gaming

Although the studies presented in the previous section indicate a link between technology use and attention problems (Christakis, 2016; Kostyrka-Allchorne, Cooper, & Simpson, 2017a; Nikkelen et al., 2014), in the case of playing action video games (AVG) it appears that, to the contrary, this activity may sharpen attention. AVGs are fast-paced games, characterised by high perceptual, cognitive, and motor demands and requiring constant prediction of future events while providing constant feedback and reward.

1.4.1. Video-gaming trains visuospatial attention

In the last two decades, there has been an interest in the possible cognitive benefits that playing video games may have. The interest came from a series of experiments conducted by Green and Bavelier (2003) on the effects of AVG playing on visual attention, where they compared AVG players and non-AVG players on a Flanker compatibility task (interference resolution), an enumeration task and a useful field of view task (spatial attention). The results strongly suggested that AVG experience enhanced the capacity of the players' visual attentional system. Subsequently, Green and Bavelier and other lab groups have replicated and extended the number of tasks these benefits were seen in, including visual search skills (Castel, Pratt, & Drummond, 2005), distribution of visuospatial attention capacities (Green & Bavelier, 2006a), visual acuity across all eccentricities (Green & Bavelier, 2007), and multiple object tracking (Green & Bavelier, 2006b). More studies followed and replicated the visual attention expertise on habitual AVG players [see a review of Bavelier et al. (2012) and a meta-analysis by Bediou et al. (2018), but also a re-analysis and critic by Hilgard, Sala, Boot, & Simons (2019)]. A causal link between AVG playing and improvements on aspects of visual attention has also been demonstrated by means of experimental training studies, where naive players undertook an intervention with AVG that increased their attentional abilities (Green & Bavelier, 2003; 2012). The effect of AVGs has also been shown to some extent in children older than 6 years (Trick, Jaspers-Fayer, & Sethi, 2005), but not younger.

1.4.2. Video-gaming benefits seem specific to top-down attention control

It is still debatable whether improvements of AVG playing are seen in low-level attention processing or higher-order attention control. Although some of the early evidence of benefits of AVGs were seen in tasks that used relatively high-salience targets to test spatial attention (e.g. the useful field of view or the Swimmer Task), benefits were later demonstrated in tasks were targets were relatively low-salience, and where serial processing was needed (e.g. Castel et al., 2005; Dye, Green, & Bavelier, 2009b; Green, Pouget, & Bavelier, 2010). When studies attempted to investigate particularly exogenous attention between AVG players and controls they have found similar (or even lower) levels of attention capture between groups (Castel et al., 2005; Dye, Green, & Bavelier, 2009b; Green et al., 2010; West, Al-Aidroos, & Pratt, 2013). These results have always been coupled with changes in top-down attention, which led researchers to the general consensus that AVG players are faster at establishing stimulus-response mappings, allowing more efficient integration between bottom-up and top-down selection processes (Castel et al., 2005). In line with this hypothesis, West, Stevens, and Pratt, (West, Stevens, Pun, & Pratt, 2008) found an increased sensitivity to exogenous stimuli in AVG players, but also explained their results by a more efficient integration between stimulus-driven and top-down processes, shown clearly by the authors in a later study (West et al., 2013). Thus, the current general consensus is that the positive effects seen with AVG play are greatest on tasks where successful performance is attributable to top-down attention or executive processes that control and regulate attentional allocation and resource management (Bediou et al., 2018; Green & Bavelier, 2012).

AVG experience has also been shown to be related to brain plasticity in areas responsible for attention and EF (e.g., Erickson et al., 2010; Kühn, Gleich, Lorenz, Lindenberger, & Gallinat, 2014; Tanaka et al., 2013), and to be associated with functional integration between attention neural networks (e.g. functional connectivity between salience and central executive networks; Gong et al., 2016). The consensus is that AVG exposure does not affect low-level sensitivity to exogenous stimuli *per se*, but that faster parallel-processing skills and quicker reaction times (P. M. Greenfield, DeWinstanley, Kilpatrick, & Kaye, 1994) can occur through enhanced top-down modulation (Castel et al., 2005; Dye, Green, & Bavelier, 2009b; Green & Bavelier, 2012; Hubert-Wallander, Green, Sugarman, & Bavelier, 2011b).

The extent to which the attention control benefits driven by AVG extend to EFs has only been examined in a few studies. Generally, the evidence supports the idea that AVG playing is associated with increased CF (faster switching between tasks; Boot, Kramer, Simons, Fabiani, & Gratton, 2008; smaller switching costs; Colzato, Van Leeuwen, Van Den Wildenberg, & Hommel, 2010; Karle, Watter, & Shedden, 2010), WM (Colzato, van den Wildenberg, Zmigrod, & Hommel, 2013), and cool-IC (faster but not more impulsive and equally capable of sustaining their attention; Dye, Green, & Bavelier, 2009a). However, these enhancements in EF are thought to be a result of faster endogenous reconfiguration processes due to a relative benefit in selective attention (Karle et al., 2010).

1.4.3. The benefits of video-gaming are specific to action video games

The improvements and transferability found for visual perceptual abilities and attention control attributed to action video games are thought to not extend to other videogame types, for example, *Tetris* or *The Sims* (Bavelier et al., 2012; Castel et al., 2005; J. E. Cohen, Green, & Bavelier, 2007; Dye & Bavelier, 2010; Dye, Green, & Bavelier, 2009b; Green & Bavelier, 2003; 2006a). The effects of action video games are thought to be the result of the complex, dynamic, stimulating, and tailored "training" environment delivered by these games. It is unclear whether this AVG environment can be put in parallel with the stimulating and contingent environment of a touchscreen game for very young children.

In this regard, the literature on computer/interactive cognitive training with very young children has provided some interesting findings. Conventional computerized training protocols, targeting EFs, including attention control, through engaging game-like tasks that require point-and-click or a joystick, have been moderately successful in enhancing EFs abilities in pre-schoolers, and provided some modest transfer effects, (e.g. Rueda et al., 2005; Thorell, Lindqvist, Nutley, Bohlin, & Klingberg, 2009). For example, Rueda and colleagues have examined the efficiency of attentional networks in 4- and 6-

year-old children before and after 5 days of computer exercises (including anticipation, WM and conflict resolution, all requiring executive attention) or interactive video experience. They found improvements in the executive attention network in the experimental group in comparison to the control group.

It is thought that, in even younger children, the effects are stronger and more widespread (transfer of training), at least for attention and WM (Wass & Scerif, 2012), and can be seen even in infancy with the right methods (ones that do not require verbal instructions and interaction with keyboards or buttons). This is the case of a study which administered a gaze-based training intervention in 11-month-old infants (Wass et al., 2011). In this study a short training period comprising of gaze-contingent (eye-tracking based) attention control training tasks led to improvements relative to an active control group in attention flexibility, sustained attention, processing speed (reduced saccadic reaction time latencies), and attention disengagement. It is noteworthy that for the active control condition the authors used a set of infant-appropriate television clips and animations. Given that the training battery was also a set of infant-appropriate screen-based tasks, with similar audio-visual features (colourful animations and engaging sounds), it is plausible to hypothesise that the self-paced contingent nature of the tasks played an important role in the success of the training protocol. The authors hypothesised that the results could be driven by a more immersive experience provided by the gaze-contingency compared to "point-and-click" computerized tasks applied by other studies; which is something that AVG authors also argue as an important factor in the cognitive enhancements found. In relation to the current thesis, I argue that the touchscreen interface can be considered an interactive and embodied experience for young children, and thus might be comparable to the training environment provided by AVG (demanding, personalised, arousing) and reproduce comparable effects. Even if in adults and older children the enhancements of attention are seen more specifically in relation to action, first-person, video-games; it might be that in infancy and early childhood, the interactivity and demands for control and agency provided by the touchscreen devices are sufficient to evoke some training of top-down attention and promote its development and widespread transfer effects.

1.4.4. Pathway of influence: learning to learn

Players of action video games (interactive and cognitive demanding media) have generally shown improvement of attentional resources and better allocation of them over a visual scene (see above). The mechanisms to support the effects found are attributed to an enhancement of probabilistic inference (Green et al., 2010) and dynamic retuning of connectivity across and within different brain areas, i.e. learning to learn (Bavelier et al., 2012).

Drawn specifically from action video games research, the proposal is that richness of video games aids learning and brain plasticity (Bavelier & Davidson, 2013; Mayo, 2009) because it provides the ideal environment for it: arousing events, frequent reward, structured scenarios and storytelling, a big variety of emotional, attentional and cognitive states, active learning across multiple contexts and domains, and constant update of challenging (yet achievable) goals. It remains to be shown if similar conditions, and effects, might arise from the interaction with the wide market of applications and games that are provided on a touchscreen device.

1.5. Literature on touchscreen media

Research into the associations between individual differences in use and access to touchscreen media platforms and attention and EF abilities are less well-documented compared to conventional media. However, some contemporary experts in understanding the potential impact of digital media impact on development have argued that modern touchscreen platforms might be a more developmentally appropriate media (compared to television) due to its interactive nature (Christakis, 2014; Geist, 2014; Zimmermann et al., 2017), which could promote development through active exploration in the same way as traditional toys (Christakis, 2014), and support learning through personal and contingent responses (Kirkorian, 2018)

Some authors have started to investigate whether the disruption to children's EF found after viewing fast and/or fantastical programming on television (e.g. Kostyrka-Allchorne, Cooper, & Simpson, 2019a; Lillard, Drell, Richey, Boguszewski, & Smith, 2015a) would also be found in the context of touchscreen interactive devices. This is the case of an experimental study by Li and colleagues (2017) with 4- to 6-year-olds, where they examined the immediate effect of exposure (either viewing or interacting) to fantastical content on children's IC. Their results revealed that only children who watched fantastical content on a non-interactive laptop screen had reduced levels of IC (poorer performance on a Go/No-go task) while children who interacted via touch with such content on an iPad did not.

With the same goal in mind, Huber and colleagues (2018) investigated EF performance before and after a screen intervention on an iPad. Toddlers aged 2 to 3 years who played with an educational app during the intervention had generally improved WM performance relative to children who watched a cartoon or an educational show. Additionally, more children in the group who played the educational app (84%) successfully delayed gratification relative to the group who watched a cartoon show (61%) or the group who watched an educational show (63%). Generally, this study showed that interacting with educational content on an iPad may have positive effects on 2- and 3-year-olds' EF, relative to watching educational or entertainment content.

In a very recent study, based on a quasi-experimental correlational study, McNeill and colleagues (2019) investigated whether preschoolers' (3- to 5-year-olds') naturalistic experience with conventional (program viewing, including if watched on a touchscreen device; *passive use*) and interactive (playing with *apps* on touchscreen-like platforms, *active use*) media was associated with lab-measures of EF (WM, IC, and CF) one year later. Contrary to previous literature that suggests a negative association between program viewing on a television set and EF, the study did not find a longitudinal association between passive use and EF (potentially suggesting that program viewing on a touchscreen produces differential effects as program viewing watched on a non-interactive platform). However, high active users (> 30 min/day) showed poorer inhibitory control (cool-IC, indexed by performance on a Go/No-go task) one year later, relative to low users and non-users. The authors suggested that high use of touchscreen devices to play games and apps might be associated with disrupted development of IC, by means of influencing the development of brain regions and neurochemical pathways sensitive to instant external reward and feedback (McNeill, Howard, Vella, & Cliff, 2019). The study did not present results concerning associations between concurrent media exposure and EF (cross-sectional relationships), neither dissociated effects from screen (television) and touchscreen media habits.

Digital media and development experts had speculated over potential benefits of interactive platforms for learning and cognition, but only a few research pieces have contributed to the study of the potential implications to attention and EF, and generally provided mixing effects that do not differentiate the unique potential impact of habitual use of these devices. One key assumption that researchers in the field made about touchscreen use is that the platform is used in the context of a well-designed interactive app, which is often not the case. Another assumption made is that watching a video on a touchscreen provides the same experience (and effects) that watching the same video on television does. The few attempts to investigate the ways touchscreen influence perception and cognition have suggested differential effects between the use of a touchscreen and television. It seems that some of the effects found with conventional media and the pathways of influence derived from it might not be readily applicable to touchscreen platforms, even if the same content is presented there. It is therefore essential to take a step back and address how the use of touchscreen media platforms, as a medium, by young children, might be associated with direct measures of children's cognitive development.

1.6. Chapter conclusions and aims of this thesis

Aim 1. To investigate the development of visual attention, dissociating between cognitive measures of stimulus-driven and goal-driven attention, in infants, toddlers, and pre-school children with different levels of touchscreen media use

The evidence from the media use literature presented above suggests that attention, specifically top-down control, develops somewhat atypically following experience with different types of screen media. Whilst watching television has often been found to be associated with everyday attentional impairments in younger children; in adults, adolescents, and older children, (action) video-gaming has been found to improve performance on many lab-based attentional skills. Only a few studies have taken methods and analytic approaches that disentangle the specific aspects of attention the atypical performance is tied to, but there is a general consensus that impairments or benefits are related to endogenous attention control.

To my knowledge, research has not applied neurocognitive methodologies to investigate the impact that modern mobile touchscreen devices (a fundamentally different platform) have in the development of attention control. This is important if we are to understand whether theories and models gleaned from attention research on the effects of television viewing or video-gaming are applicable to touchscreen use, and thus better inform policy-makers and parents. In Chapter 3 and 4, I aim to address this gap by studying attention across development, dissociating exogenous and endogenous aspects of attention, within a prospective study of children with different levels of use of touchscreen devices. Specifically, I ask whether concurrent high users of touchscreen devices show differential performance levels of exogenous or endogenous attention; and the extent to which the interplay between exogenous and endogenous attention in situations of conflict is associated with stable use over time. I answer these questions making use of a screen-based eye-tracking methodology, to study contingent visual attention in the context of visual search (Chapter 3) and in the context of saccadic control (Chapter 4).

Aim 2: To investigate executive function performance in children with different levels of touchscreen media use

Child-appropriate gaze-contingent tasks provide useful insights into neurocognitive attention profiles. They tend to make more use of audio-visual salient changes and arousal-inducing features, so are more likely to be influenced by low-level perceptual individual abilities and susceptibilities. This is an important consideration in the context of the main question of this thesis, given that digital content constantly makes use of the same audio-visual features. Behavioural tasks using three-dimensional stimuli and rule-based performance, in play-like contexts, are likely to prompt more higher-order cognitive processing (Choudhury & Gorman, 2000; Wass, 2014b) and impose more demands on executive functioning. A key aim of this thesis was to investigate "real-world" EF performance in children with different levels of use of touchscreen devices. Research to date points generally to a longitudinal negative impact of mobile active touchscreen devices use (similar to television effects) on inhibitory control, but a question remains of whether concurrent use (including viewing videos or playing apps) of a touchscreen device is also associated with EF. In Chapter 5, I aim to answer this question by investigating whether different levels of concurrent touchscreen use are associated with performance in executive functions, specifically working memory, inhibitory control, and cognitive flexibility. I answer this question using a combined data-driven and theory-based approach to first understand the structure of EF in pre-school, making use of behavioural (table-top) and cognitive-based (touchscreen-based) conventional measures of EF.

This work will, I hope, be immediately useful in identifying whether the recreational use of mobile touchscreen media by infants and toddlers shows any association with their attentional and executive behaviours. I hope it will, in the future, inform policy-making and parents' guidelines, by providing rigourous empirical evidence based on detailed neurocognitve measures of child development to address a timely question. It should also be of value in the longer-term effort of demonstrating causality and direction of media effects, and of understanding the development of attention and EF across the first years of life in relation to environmental sources of influence, by identifying potential specific measures associated with levels of media use that can be targets of experimental interventions in hypothesis-driven research studies.

Embedding research within a longitudinal study has major benefits over a cross-sectional design, by enabling understanding of developmental processes and underlying mechanisms, and potentially informing about timescales and sensitive periods around atypical trajectories (Karmiloff-Smith, 1998; Paterson, Parish-Morris, Hirsh-Pasek, & Golinkoff, 2016), driven by the environmental influence of touchscreen media use. My focus in this thesis is on the first years of life, in the period from 12 months to 3.5 years, as this is 1) the period when executive control emergent abilities undergo considerable development (Conejero & Rueda, 2017; Hendry et al., 2016) and EF distinct processes start to be observable (Garon et al., 2008); and 2) the most susceptible period for the varied pathways of influence to take place and alter normal trajectories of cognitive development (Christakis et al., 2012; Kostyrka-Allchorne, Cooper, & Simpson, 2017a; Wass & Scerif, 2012; Werchan & Amso, 2017).

While passive (television viewing) and active (video-gaming) media use have shown obvious distinct effects on cognitive development, modern platforms (i.e. touchscreen devices) can provide both types of use, and, as seen in section 1.2, these devices are being used by young children for a wide range of activities, in varied contexts, and coupled with multi-media use. The interactive experience provided by touchscreen-like platforms, even when used to watch short movie clips, promotes a sense of agency (the flow of content depends on the user behaviour, by providing opportunity for personal and contingent responses) and a more embodied experience (guiding attention and motor responses to relevant information on the screen). Therefore, it is not clear yet whether passive and active experiences on a touchscreen differ fundamentally from that experience on conventional media, and so parallels with conventional media to establish and formulate strong hypothesis is largely restricted.

There are two main reasons why touchscreen media use, in this thesis, was operationalized independently of content or activity:

1) Novelty of the platform. There is a scarcity of previous literature on the topic of attention and EF relationships with naturalistic observations of touchscreen mobile media use, and literature on conventional media is insufficient to provide a solid background upon to formulate strong predictions. The first logical step is therefore to test for potential associations with neurognitive measures of attention and EF in broadly defined groups (low vs high users of touchscreens), so that future studies can investigate specific hypothesis in relation to the groups differences found (e.g. address content of use to follow-up on previous findings).

2) Defining types of (touch)screen time. Touchscreen content can come in many different forms, and methods to categorise and quantify the types of use that can happen on the device, and how they change with age and experience, are not yet established (although initiatives to study mobile touchscreen patterns in adults are showing promising

results; Reeves et al., 2019). Even defining active or passive use on a touchscreen proves difficult: e.g. is watching *Peppa Pig* on YouTube in auto-play passive or active use?; and categorising appropriateness (i.e. educational value) of content is also prone to biases in the market ratings (Hirsh-Pasek et al., 2015). In addition, it is practically (and ethically) impossible to get a direct accurate quantifiable measure of the content and context of touchscreen use (i.e. track multiple family devices and reliably assess who is using the device at any point in time), that is not biased to parent-report bias and their own definitions of content. To overcome these issues, one would need large sample sizes and an hypothesis-driven approach – which would not be appropriate given the state of the art of the field (see previous point).

Therefore, in this thesis, touchscreen media use (such as the use of tablets, smartphones, and touchscreen computers) will be studied in relation to the quantity/amount of use per day by infants and toddlers, independently of *where*, *when*, with *whom*, and *why* that use happened. It will be operationalised in terms of parent-report answers and recoded as a dichotomous variable of low or high touchscreen use. In the next methodological chapter I will provide a detailed description of this methodological approach, its limitations and how they were overcomed, and provide information about the TABLET sample and its media environment; with the aim that this contextualization will benefit discussions of findings in the next chapters and better support the conclusions arising from them.

Chapter 2:

General methodology – The TABLET Study

2.

2.1. Introduction – Why is this chapter needed?

The data presented in this thesis is part of a longitudinal project, the Toddler Attentional Behaviours and LEarning with Touchscreens (TABLET) project[3], set up to investigate the associations between early touchscreen use and a range of developmental outcomes in infancy, toddlerhood, and pre-school. This was a Leverhulme and Wellcome Trust-funded UK-based project started in 2014, where families participated via two waves of online questionnaires assessing media use, developmental milestones (Bedford et al., 2016), sleep (Cheung et al., 2017), temperament, and adaptive behaviours; and three waves of lab-visits to the Centre for Brain and Cognitive Development at Birkbeck (the London *BabyLab*). This chapter will provide a summary of the TABLET lab-based stream, contextualize and describe its study design, including providing an overview of the recruitment procedure, its main rational (i.e. touchscreen group coding), and the benefits, challenges, and limitations associated with this approach. I also aim to describe in this chapter the TABLET sample at each age point, and to provide an overview of the media environment in each of the touchscreen media use groups. I hope this information will benefit discussions of findings in the next chapters. A third part of the current chapter will outline the general lab-assessment protocol at each age visit, and the main longitudinal analytical tools used in this thesis, while specific details on the individual paradigms and analysis are reported in the relevant chapters.

2.2. General methodological background

Quasi-experimental design studies of naturalistic behaviours

The TABLET project lab-study takes a quasi-experimental design to study the impact of touchscreen exposure in infancy to the pre-school years. In this project, and throughout this thesis, the key quasi-independent variable is a touchscreen use grouping variable with two levels (based on a cut-off median score, see below 'Touchscreen Media Use: Group coding' section). As a quasi-experiment, it lacks the element of random assignment of children to the different "treatments", i.e. in this case, exposure levels of touchscreen media use. Given that the groups compared may not be matched at baseline

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[3] *https://www.cinelabresearch.com/tablet-project*

in observed and unobserved variables, it is subject to concerns regarding internal validity, i.e. a causal link between touchscreen exposure and observed outcomes (in the case of this thesis, attention and EF) cannot be demonstrated from this design (Morgan, Gliner, & Harmon, 2000). Furthermore, in the case of the studies within this thesis, the key touchscreen group variable was not "fixed" over time (touchscreen use changed across visits) and so the analysis applied in the studies vary between cross-sectional analysis (when associations are estimated at each visit based on between concurrent touchscreen use and the outcomes variables), and longitudinal analysis (when associations between touchscreen use at previous visits and the outcomes variables at each visit are estimated). Cross-sectional designs help in the identification of associations between media use and cognitive outcomes but do not further understanding of directionality of effects, causality or mechanisms that explain the associations found. In contrast, longitudinal research holds the potential to explain some temporal order of associations and provide insights on possible causal mechanisms. However, only a full experimental design, specifically a randomized control trial, can scientifically demonstrate a causal relationship.

While quasi-experiments have considerable scientific limitations in terms of the ability to draw causal inferences and the possibility of confounding bias (Morgan et al., 2000), they are very useful in areas where is not feasible or ethical to conduct an experimental or randomized control trial, such as those cases where the aim is to evaluate the impact of a climactic societal change; they also provide valuable information as a first step towards solid research in a new field, and present ecological validity (findings may be generalized to other populations). The limitations can be reduced by matching participants recruited on potentially relevant variables (variables that are either related to the independent variable or the outcomes) and/or using modeling techniques that take into account the effects of these confounding variables.

Measuring screen time

Screen time is not a unitary phenomenon and can take many forms, which likely have differential impacts on cognitive development. For infants, toddlers, and pre-school children, it can vary from watching a movie, chosen or not by the parent but most likely set up by them, on a TV set in the living room, to playing with a digital puzzle on an iPad. As it has been shown in the introductory chapter of this thesis, the evidence from media studies has consistently shown a very different impact on cognitive development from different conventional media like television viewing and playing video-games. Modern media platforms, like mobile touchscreen devices, are a novel medium that may have, too, a fundamentally different impact on health and wellbeing (D. R. Anderson & Davidson, 2019; Christakis, 2014). A critical first step to understanding the potential role of mobile touchscreen media on the development of attention and executive processes is thus to first establish associations between broad touchscreen media exposure and specific aspects of said processes.

However, measuring naturalistic behaviours, such as screen habits, is complex. The most accurate way to measure screen time in young children would be to objectively track the child's multi-screen media exposure, using passive sensing systems embedded within home TV sets (Meister, 2018) and within mobile handheld devices of parents (G. Miller, 2012; Reeves et al., 2019); which necessarily need to make use of face-recognition algorithms that can reliably inform who is using the screen (i.e. the research participant, a sibling, or the parent), or use child's point-of-view video cameras (e.g. L. B. Smith, Yu, Yoshida, & Fausey, 2015). Whilst accurate, this option is unfeasible for research studies with children, given the practical, technical, and ethical (i.e. privacy) challenges.

With no other options, a great amount of research addressing the media impact on physiological and psychological outcomes settle on using retrospective self/parent-report measures of media use. This is usually taken in the form of a question, or a set of questions, about frequency and duration of different media habits, which have shown adequate internal consistency and test-retest reliability (Carson et al., 2017). In studies with younger children, this question is usually directed to the primary caregiver. This is the most common approach used in the studies reviewed in the introductory chapter, and the approach currently taken in this thesis studies. A key limitation of this approach is that parent-report measures, based on recall or generalization of a typical day, are thought to be imprecise, due to poor recall and respondent's bias to give socially or individual desirable answers (Morsbach & Prinz, 2006). However, it is still expected the variation across families to be positively correlated with their actual screen time (as shown in prior studies, e.g. D. R. Anderson, Field, Collins, Lorch, & Nathan, 1985; Lin et al., 2015). Another popular option for measuring "screen time" is using media diaries, which can allow examination of children's media diet by categories of content, and rely on accurate information recorded in a specific day rather than generalizations (D. R. Anderson et al., 1985). These can be self-report or parent-report daily sheets, divided into blocks of time that contain spaces for several items of information, including the type of media, name of program, and context of the media activity.

2.3. ***The TABLET lab-stream study design and sample characteristics***

2.3.1. Overview

The TABLET study lab-stream design is in its essence a prospective cohort study, with a quasi-experimental design. Fifty-six infants were initially recruited for the study with the primary aim to study differences between two groups of users that differed distinctly in touchscreen exposure. At the time of the study design, the sample size could not be directly powered because no similar studies addressing touchscreen use impact on neurocognitive measures had been carried out. Thus, sample size was chosen to match previous related studies, including longitudinal between-subjects quasi-experimental studies on the associations between early childhood exposure to television and cognitive skills [60 children recruited in a two (two content types) by two (two levels of exposure) between-subjects design (Barr et al., 2010)], and to overrecruit based on specific studies describing the paradigms used in this thesis: infant Visual Search (17 typical developing toddlers and 17 toddlers with Autism Spectrum Disorders; Kaldy, Kraper, Carter, & Blaser, 2011), and infant Anti-saccade (20 typical infants in the original experiment by Johnson, 1995); to accommodate scheduling difficulties and child fatigue.

While the sample size does not allow a powered analysis to dissociate different types of use, it seems of value that before investigating the type of use on a touchscreen one should first show the impact of general use. Investigations dissociating the content, context, and child characteristics that play a role in media effects are an ideal approach in the field, but best achieved in large sample studies (Bedford et al., 2016), which are logisitically unfeasible with a neurocognitive approach (required to study attention and EF). As such, the approach of the TABLET lab-based study is to initially assess broadly defined group differences (i.e. high vs low levels of touchscreen exposure), so that hypothesis-driven measurements targets can be derived and tested in large-scale future studies.

Ethics, consent, and permission

Ethics approval for the TABLET study was granted by the Birkbeck Psychological Sciences' ethics board. The lab visits at 12 and 18 months were approved in June 2015 (Ref 141570), and the 18 months visit was conducted after an amendment in May 2016. The lab visit at 3.5 years was approved subsequently, in December 2017 (Ref 171821). Parents gave written informed consent to participate at all time points. The Birkbeck Psychological Sciences' ethics board operate according to the British Psychological Sciences, ESRC ethical guidelines and adhere to the Declaration of Helsinki.

2.3.2. The TABLET lab-sample

Recruitment

Fifty-six infants were recruited for the TABLET project, between October 2015 and March 2016. The majority of families were contacted after taking part in the TABLET online questionnaire (Bedford et al., 2016; Cheung et al., 2017), which was advertised via the Birkbeck Babylab database, the Goldsmiths' Babylab database and study advertisements from various news agencies, magazines and agencies including the National Childbirth Trust. Parents in the London Area with infants approaching 12 months were contacted by e-mail, or by phone if they were not responsive. Parents were given information about the study and the longitudinal aspect of the assessments, before agreeing to participate. If the parent agreed to participate, the visit to the Birkbeck Babylab was scheduled within 1 month of the infant's first birthday (except for one case where the infant was 14 months at the time of the first visit). Whenever possible, the visit was scheduled a few days before the birthday to accommodate for re-scheduling.

Families were invited to take part in the follow-up visits when children were 18 months and 3.5 years, except if they specifically requested not to be contacted for future visits – see Figure 2. 1. Parents were contacted again to confirm their agreement to participate and to schedule the upcoming visit. Infants were tested within 1 month of the ideal age (18 months, 41 months), but, if no other scheduling options were possible, infants were occasionally allowed to be slightly out of the age range on the day of testing. This happened for 6 infants at the 18 months visit who were 16 months, and for 1 child at the 3.5 years visit who was 43 months. These exceptions were adopted to minimise data loss at the follow-up visits.

Figure 2. 1. Infants came to the Babylab in London at 12 months, 18 months, and 3.5 years.

Approximately one week before each scheduled visit, questionnaires about the child's media environment (Bedford et al., 2016), sleep (Sadeh, 2004), temperament (very-short IBQ; Putnam, Helbig, Gartstein, Rothbart, & Leerkes, 2014; very-short ECBQ; Putnam, Jacobs, Gartstein, & Rothbart, 2010; short CBQ; Putnam & Rothbart, 2010), and a media diary (see details below in 2.3.3 The TABLET sample media environment'Media diaries') were sent to the parent by email. On the day of the visit, parents were welcomed by the experimenter and the testing procedure was thoroughly explained to them. Parents provided written informed consent at each time point before the testing protocol took place. At the end of the experiment, children were given a *Babylab* T-shirt as a gift, and parents were reimbursed for journey expenses. Only families that were able to come to the *Babylab* on a day for their child to be tested were included in the analyses within this thesis.

Participants

From the fifty-six infants initially recruited three participants were excluded from the study: one due to withdrawing of consent after the first visit and the other two due to later diagnosis of genetic (Angelman syndrome) or neurological (mild cerebral palsy) conditions.

For the analyses presented in the next chapters a total of 53 12-months infants (23 girls, M = 376 days/ 12.4 months, SD = 20 days), 49 18-months toddlers (22 girls, M = 540 days/ 17.8 months, SD = 21 days) and 46 3.5-years children (23 girls, M = 1256 days/ 41.3 months, SD = 16 days) were included. A breakdown of the sample by longitudinal visit can be seen in Table 2. 1 to Table 2. 3 along with detailed descriptive statistics.

The socioeconomic status of the sample, indexed by maternal education, was relatively high and homogenous, with 92% of mothers holding a university or postgraduate degree. One child in the sample was born prematurely at 32 weeks and one child was reported to occasionally suffer from Reflex Anoxic Seizures; as both were able to fully perform the tasks required their data were retained in the analysis.

Table 2. 1. Descriptive and frequency statistics for high and low touchscreen media users at 12 months.

<u>Visit at 12 months</u>	Sample	Low users (<10 min/day)	High users (≥10 min/day)	Between-groups comparison
N	**53**	**21**	**32**	
Touchscreen use (min/day)	**26 (55)**	**0.5 (1)**	**42 (66)**	***p* = 0.001**
Gender				
Girls	23 (43%)	12	11	n.s. (0.102)
Boys	30 (57%)	9	21	
Mother's Education				
School leaving or college	4 (7%)	1	3	n.s. (0.565)
University or postgrad	48 (91%)	19	29	
Missing, N/A	1 (2%)	1		
Age (days)	376 (20)	374 (19)	378 (20)	n.s. (0.426)
Background TV (min/day)*	180 (171)	151 (170)	199 (172)	n.s (0.323)
MSEL Standard Score	108 (11)	110 (10)	107 (12)	n.s. (0.446)
IBQ/ECBQ				
Effortful Control	4.75 (0.88)	4.59 (1.02)	4.85 (0.78)	n.s. (0.313)
Negative Affect	3.40 (1.27)	3.33 (1.25)	3.45 (1.30)	n.s. (0.755)
Surgency	5.10 (0.64)	5.18 (0.45)	5.04 (0.73)	n.s. (0.437)

** One value that exceed 3 standard deviations from the mean was trimmed (i.e. changed to be one more than the non-trimmed highest value)*
MSEL = Mullen Scales of Early Learning; IBQ = Infant Behavior Questionnaire; ECBQ = Early Childhood Behavior Questionnaire

Table 2. 2. Descriptive and frequency statistics for high and low touchscreen media users at 18 months. User groups differ in background TV: High users parents' reported more Background TV.

<u>Visit at 18 months</u>	Sample	Low users (<15 min/day)	High users (≥15 min/day)	Between-groups comparison
N	**49**	**23**	**26**	
Touchscreen use (min/day)	**29 (62)**	**2 (3)**	**53 (79)**	***p* = 0.003**
Gender				
Girls	22 (45%)	13	9	n.s. (0.124)
Boys	27 (55%)	10	17	
Mother's Education				
School leaving or college	3 (6%)	2	1	n.s. (0.502)
University or postgrad	45 (92%)	21	24	
Missing, N/A	1 (2%)		1	
Age (days)	540 (21)	536 (19)	544 (22)	n.s. (0.165)
Background TV (min/day)	**146 (124)**	**105 (112)**	**182 (124)**	***p* = 0.030**
MSEL Standard Score	111 (18)	113 (18)	108 (18)	n.s. (0.364)

MSEL = Mullen Scales of Early Learning

Table 2. 3. Descriptive and frequency statistics for high and low touchscreen media users at 3.5 years. User groups differ in background TV: High users parents' reported more background TV.

<u>Visit at 3.5 years</u>	Sample	Low users (<15 min/day)	High users (≥15 min/day)	Between-groups comparison
N	**46**	**19**	**27**	
Touchscreen use (min/day)	**38 (63)**	**3 (4)**	**62 (73)**	***p* < 0.001**
Gender				
Girls	23 (50%)	12	11	n.s. (0.134)
Boys	23 (50%)	7	16	
Mother's Education				
School leaving or college	3 (7%)	0	3	n.s. (0.125)
University or postgrad	42 (91%)	19	23	
Missing, N/A	1 (2%)		1	
Age (days)	1256 (16)	1257 (14)	1256 (18)	n.s. (0.781)
Background TV (min/day)	**169 (140)**	**112 (147)**	**208 (123)**	***p* = 0.022**
MSEL Visual Reception	65 (10)	62 (9)	67 (10)	n.s. (0.093)

Touchscreen Media Use: Group coding

To assess touchscreen usage, parents completed an online questionnaire before coming to each visit at the Babylab, at all time points. Parents were asked about the duration of their child's use in hours and minutes: 'On a typical day, how long does your child spend using a touchscreen device (tablet, smartphone or touchscreen laptop)?' (Bedford et al., 2016). While self/parent-report measures of screen time have important limitations, including reporter bias and under-estimation (e.g. Orben & Przybylski, 2019), studies investigating the validity of self-report have shown a moderate but significant positive correlation and suggested the rank order of individual differences in screen time are captured by self/parent-report (D. R. Anderson et al., 1985; Lin et al., 2015). This supports an analytical approach that captures the degree of daily touchscreen media use in terms of levels of exposure. So, in the studies presented in this thesis, the main outcome measure of touchscreen media use is based on the sample median split (i.e. high vs. low usage). Splitting the sample in terms of a quartile cut-off system (e.g. Barr et al., 2010), or a value based on pragmatic assessments (e.g. 30 min/day of touchscreen app use; McNeill et al., 2019), is a common analytical approach when studying naturalistic media use with modest sample sizes. Besides, because a dosage effect of touchscreen use on attention or EF outcomes was not available at the time of the study design, and because the top quartile approach naturally leads to imbalanced group sizes, it was opted early in the project design to use the median cut-off. However, when appropriate, regression analysis with the continuous duration of use will be reported to address dosage-dependent effects.

Usage group classification was computed based on the sample median of the parent-report daily touchscreen time at each age point. Children who were in the top cut of exposure were coded as "high users" whereas the children in the low cut were coded as "low users". At 12 months, when children were recruited to the study, the median cut-off was 10 minutes per day, the same as found on the TABLET large online survey (Bedford et al., 2016). The child media environment is dynamic, and likely to vary depending on age, level of development and family characteristics (e.g. change of routines such as starting attending school; Valkenburg & Peter, 2013). Usage duration was significantly associated across age, with strong associations between 12 and 18 months visits, and moderate associations between those visits and the 3.5 years visit (see Table 2. 4). Consequently, children’s user group (low or high) varied across visits. At 18 months and 3.5 years, the median cut-off was 15 minutes per day. In total, 7 children changed groups from 12 months to 18 months (2 Low to High usage, 5 High to Low usage), and 14 changed from 18 months to 3.5 years (9 Low to High usage, 5 High to Low usage). A strength of this approach is that by classifying children at each time point one can study both the longitudinal associations of touchscreen use and the concurrent ones.

*Table 2. 4. Parent reported touchscreen use (minutes/day) details for the TABLET Sample and concurrent usage groups split by age visit.*p < 0.05, **p < 0.001 for the Spearman’s rho correlation. Correlations were computed with trimmed usage values (values that exceed 3 standard deviations from the mean were changed to be one more than the non-trimmed highest value), descriptive statistics were computed with non-trimmed values.*

		12-months (min/day)	18-months (min/day)	3.5-years (min/day)
12-months (min/day)		-	0.78**	0.31*
18-months (min/day)		-	-	0.33*
Median Cut-off		**10**	**15**	**15**
Sample Mean (SD)		25.58 (54.94)	29.14 (62.28)	37.93 (62.92)
Range		0 – 310	0 – 405	0 – 380
Concurrent Low Use	N	**21**	**23**	**19**
	Mean (SD)	0.52 (1.25)	2.09 (3.23)	3.16 (4.15)
Concurrent High Use	N	**32**	**26**	**27**
	Mean (SD)	42.03 (66.01)	53.08 (78.54)	62.41 (73.03)

All parents filled the question regarding touchscreen media use at home prior to the visit, or in the lab on the day of the visit, except for two participants (one at the 18 month visit and another at the 3.5 year visit) who missed completing the questionnaires and were unavailable to reply either by e-mail or phone after the visit. For these two cases, an estimation was done based on the child’s media diaries (in both cases the parents did not report any touchscreen media use in the media diaries, so the child's use was estimated to be minimal; see below for details of the measure). Table 2. 1 to Table 2. 3 presents detailed descriptive statistics of each visit usage group, including the number of participants, touchscreen media usage and background measures. For continuous numerical variables data are presented as Mean (Standard Deviation) and difference between user groups was tested with an independent samples t-test. For categorical variables data are presented as N (Proportion) and difference between user groups was tested with a Pearson Chi-Square.

Background covariates

An effort was made throughout the project design to take into account and measure the child's and family's characteristics that could potentially confound the general findings of the work presented throughout this thesis. Background TV in the home and Mother's education (as measures of the family media environment and developmentally appropriate support, respectively), and child's age, developmental level (Mullen Scales of Early Learning score), and gender (as measures of child's traits), were matched between touchscreen media use groups at recruitment.

Mothers' education was assessed on the initial pre-recruitment online questionnaire. Parents were asked to choose the highest degree or level of education the mother of the child had completed from 5 options (i.e. Not applicable, school leaving qualification, college, university, post-graduate). Mother's education was then recoded so it would be a binary variable of below degree, or degree level or above.

General development level was assessed in the lab visits via the Mullen Scales of Early Learning (MSEL; Mullen, 1995). The MSEL is a standardised developmental assessment, administered by the experimenters, examining early motor and cognitive development from 0-68 months. An early learning composite standard score is conventionally calculated based on four subscales: visual reception (VR), fine motor (FM), receptive language (RL) and expressive language (EL). In this thesis, the MSEL standard score was used as a covariate to control for the effects of group differences in cognitive developmental level, at 12 and 18 months. At 3.5 years, only the VR subscale was administered to avoid overloading participants, so the standard score of this subscale was used as a background covariate.

Background TV in the home was assessed in minutes per day, assessed through parent-report on the online media questionnaire by asking the question: 'On a typical day, how long is a TV switched on in your home?'. Background television values were trimmed (i.e. changed to be one more than the non-trimmed highest value) if they exceed 3 standard deviations from the mean of the sample at each age point.

Concurrent Background TV, concurrent age, gender and mother's education at the age of recruitment, and concurrent MSEL composite score (or the standard score available) were tested for between-group differences at the two follow-up visits. Independent Samples t-tests were run for continuous variables and Chi-squared Tests for binary variables. Because Background TV differed between concurrent touchscreen media use groups at 18 months and 3.5 years (see Table 2. 2 and Table 2. 3), over the next chapters it will be included as a covariate in the follow-up models in a stepwise approach, i.e. it will be retained in the analysis and reported in Appendixes if it has a significant main effect on any of the outcome variables.

In addition, the very short-form version of the IBQ (Gartstein & Rothbart, 2003; 37-item measure) was filled by 31 parents and the Early Childhood Behaviour Questionnaire (Putnam, Gartstein, & Rothbart, 2006; 36-item measure) was filled by 20 parents in the pre-recruitment online questionnaire at 12 months to measure infants' temperament. Both of these questionnaires assess the infant's temperament and behaviour, and are both equally suitable for infants at 12 months. Parents are asked to rate on a 7-point Likert scale how well each item described their child behaviours related to each scale the questionnaire measures. Mean scores cover three subscales including Effortful Control, Surgency, and Negative Affect. Mean scores were combined between the two questionnaires, and recruitment groups matched in these scales. This result, particularly for Effortful Control (which is taken to index executive control of behaviour and attention, Conejero & Rueda, 2017; Kochanska et al., 2000; Rothbart, 1989), allows us to assume that baseline values for these participants were reasonably the same for both usage groups at the beginning of the experiment, therefore child's pre-susceptibilities in terms of executive attention traits are unlikely to explain subsequent results presented in relation to touchscreen use. However, these measures are less reliable and sensitive estimations the younger the child, and therefore group predispositions might differ later in development.

2.3.3. The TABLET sample digital media environment

Media diaries

In addition to answering retrospective questions about their child's media use, parents also completed one or two 24-hour diaries at all age points to complement the parent-report measurement. At 12-months, parents completed one diary at home, before the visit. The diary (see Appendix 2) was sent to them by email. At 18-months, one diary was filled in the lab and administered by the experimenter, by recalling the day before the visit with the parent. At 3.5 years, parents completed two diaries at home by filling an online questionnaire[4] (similar to the one in Appendix 2) implemented for this purpose – email notifications were sent on a weekend day and a weekday on days specified by the experimenter (usually Sunday and Thursday before the visit).

The diaries asked the parent to record, in hour-slots, the times the child was: sleeping, at nursery (for the 3.5 years assessment), watching television (adult-directed; or child-directed), or using a touchscreen [passively watching videos; actively controlling videos (e.g, swipe/select, scroll forward); calling someone; playing games; using education apps; using creative apps (e.g. drawing); listening to music; or looking at photos (for the 3.5 years assessment)]. Besides, parents were prompted to report the details of the media activities the child had engaged during the day.

The amount of time (hours/day) that participants were exposed to each type of television content (adult-directed, child-directed) and each activity on a touchscreen platform (passively watching videos; actively controlling videos; calling; playing games; playing education apps; playing creative apps; listening to music; or looking at photos) were calculated based on their media diary at 12 months and 18 months, or averaged between the two diaries (if available) at 3.5 years. Total screen exposure (either adult or child-directed TV) and total touchscreen exposure (activities on a touchscreen) were also calculated by summing the number of slots in the specific categories.

The media diaries reflected quite well the levels of exposure that were drawn from the parent-reported measures, with low users spending roughly a third of the time on a touchscreen that high users did – see Figure 2. 2. Descriptively, at 12 and 18 months, high users' additional time seemed to be spent with active and passive watching of videos (note the choice between passive and active was up to parents), while at 3.5 years they seemed to engage relatively more time with games on a touchscreen (similarly to other reports in the field, e.g. Kabali et al., 2015), while still spending more than half of the time on watching videos (passively or actively).

The time-diary estimates for television viewing also seem to go in line with the findings reported earlier, in the sense that high users tended to have higher levels of television exposure in the home – Figure 2. 3. Descriptively, while high users increased their viewing of child-directed content with age and decreased their relative exposure to adult-directed content; low users viewing was more varied with age.

[4] *Implemented in the Gorilla Experiment Builder (www.gorilla.sc; Anwyl-Irvine, Massonnié, Flitton, Kirkham, & Evershed, 2019)*

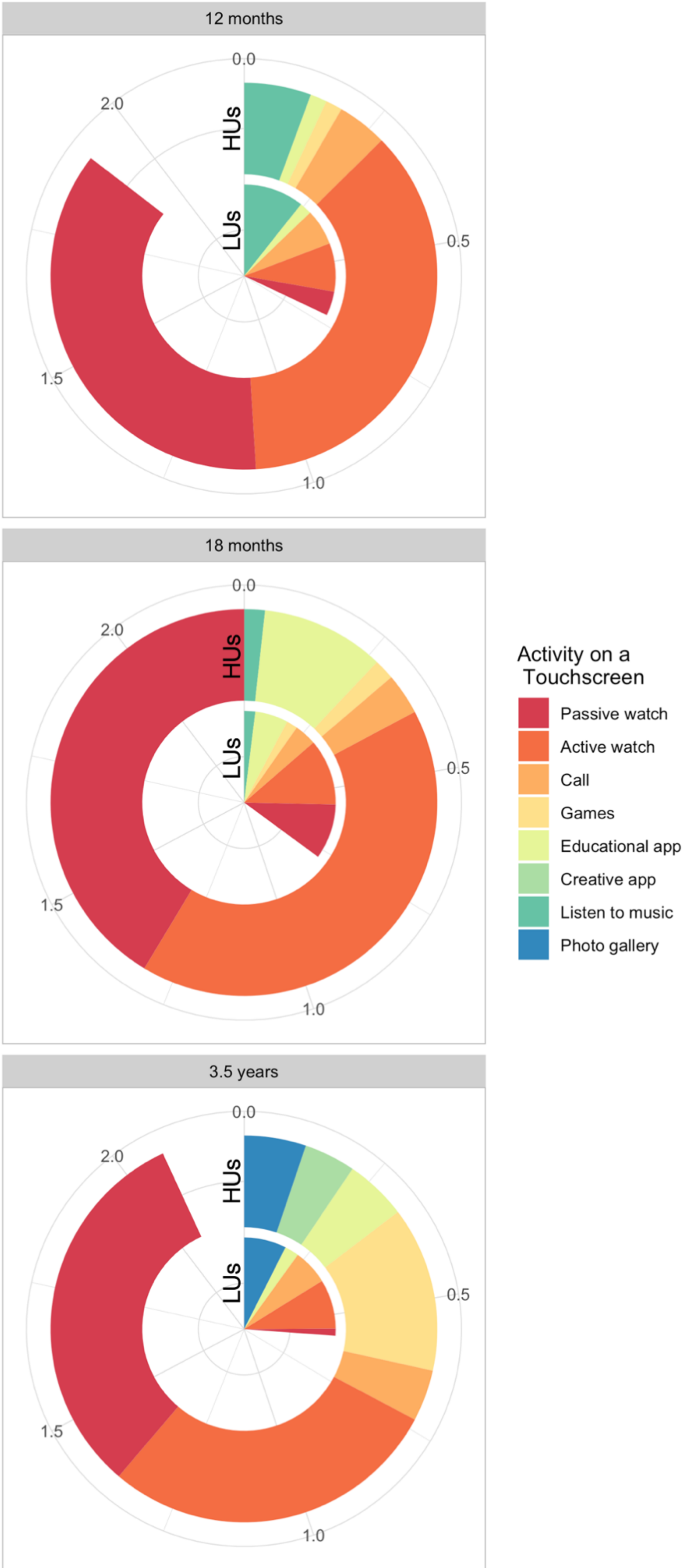

Figure 2. 2. Pie-plot of the activities done on a touchscreen during the day for high users (HUs) on the outside, for low users (LUs) on the inside of the pie. Scale is in hours/day.

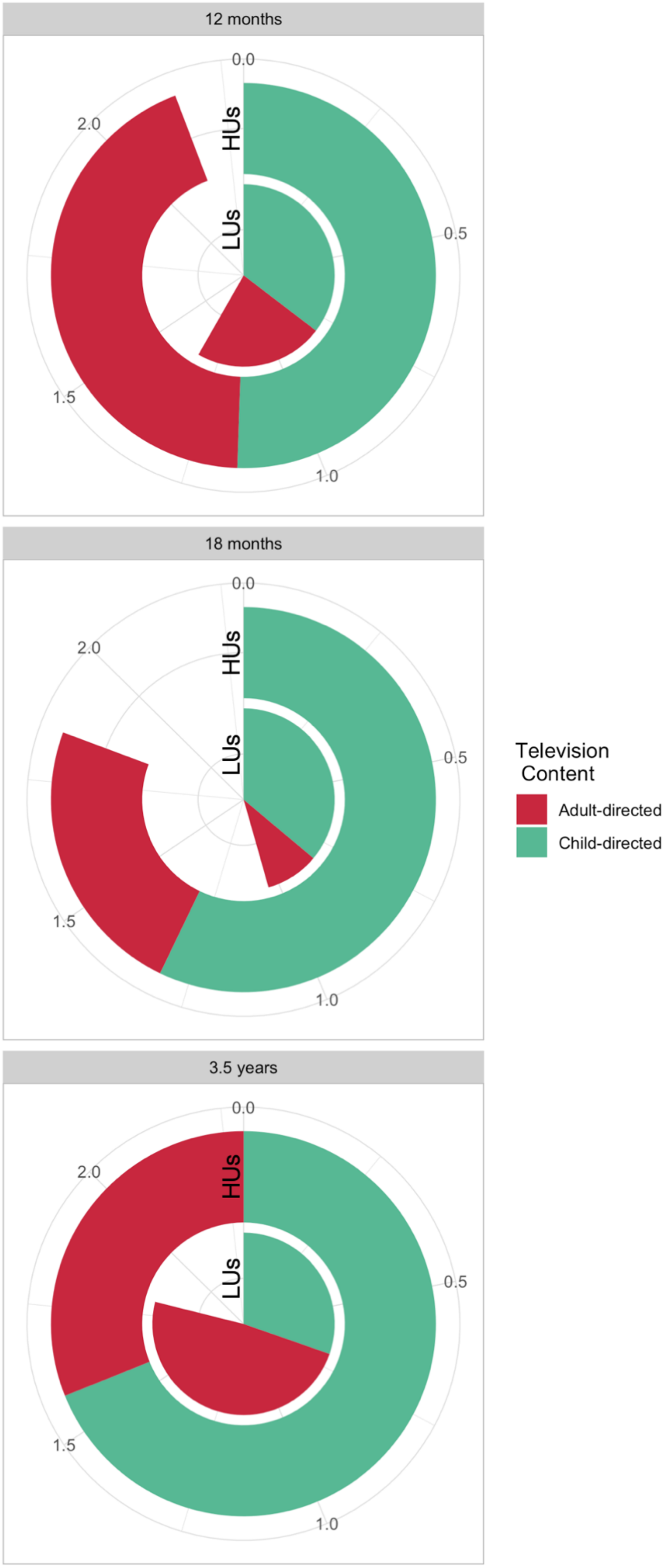

Figure 2. 3. Pie-plot of the content watched on a TV set during the day for high users (HUs) on the outside, for low users (LUs) on the inside of the pie. Scale is in hours/day.

Validation of the parent-report measure of touchscreen use

Studies investigating the validity of self/parent-report retrospective question measures of screen time have shown a moderate but significant positive correlation with precise tracking measures (e.g. using direct measures of sedentary behaviour; Lin et al., 2015; and video observation; D. R. Anderson et al., 1985). Furthermore, existing evidence suggests that data gathered using diary measures of television viewing approximate actual behaviour (D. R. Anderson et al., 1985). In the TABLET sample, the parent-report measure of touchscreen use duration was significantly and moderately (ranging from a correlation of 0.49 at 12 months to 0.62 at 3.5 years) associated with the total duration of touchscreen exposure reported on the 24-hour media diaries, which supports and validates the parent-reported measure of touchscreen use. See Table 2. 5 for cross-sectional/ concurrent correlations between the parent-report continuous measure of touchscreen use (which the key user groups are based upon) and the estimates from the media diaries.

Table 2. 5. Parent-reported touchscreen use (minutes/day) and parent-reported Background TV (minutes/day) cross-sectional (i.e. concurrent) correlations with media-diary estimates of total touchscreen time, total TV viewing time, and total TV time split by adult-directed and child-directed TV programmes viewing. Spearman's rho correlation were computed with trimmed usage values (values that exceed 3 standard deviations from the mean were changed to be one more than the non-trimmed highest value). Significant correlations are in bold.

	Questionnaire	**Media-diary estimates (hours/day)**			
	Background TV	*Total Touchscreen*	*Total TV*	*Adult TV*	*Child TV*
At 12 months					
Touchscreen use, r_s *p* *N*	0.169 0.227 53	**0.488** **<0.001** **53**	0.246 0.075 53	0.196 0.160 53	0.141 0.313 53
Background TV, r_s *p* *N*		0.195 0.161 53	**0.640** **<0.001** **53**	**0.362** **0.008** **53**	**0.458** **0.001** **53**
At 18 months					
Touchscreen use, r_s *p* *N*	**0.375** **0.009** **48**	**0.586** **<0.001** **49**	**0.309** **0.031** **49**	0.253 0.080 49	0.238 0.100 49
Background TV, r_s *p* *N*		**0.320** **0.026** **48**	**0.628** **<0.001** **48**	**0.436** **0.002** **48**	**0.489** **<0.001** **48**
At 3.5 years					
Touchscreen use, r_s *p* *N*	**0.395** **0.007** **45**	**0.619** **<0.001** **44**	**0.298** **0.049** **44**	-0.033 0.830 44	0.267 0.079 44
Background TV, r_s *p* *N*		**0.396** **0.009** **43**	**0.658** **<0.001** **43**	0.187 0.229 43	**0.481** **<.0001** **43**

Touchscreen media use (parent-report measurement), which was shown to be related with the parent-report measurement of Background TV in the follow-up visits (see in Table 2. 2 and Table 2. 3 group comparisons for Background TV), was indeed moderately related to the time-diary estimate of total TV viewing time at these visits, although it did not seem to be related specifically with the estimates of adult or child-directed TV programmes viewing (i.e. programmes suitable for, respectively, adult or child audiences). However, high and low users did not seem to differ in terms of these media-diary measurements related to television exposure, although high users tended to have higher exposure – Table 2. 6.

Furthermore, background TV, a covariate on follow-up analysis presented in later chapters, seems to be a good proxy of total TV exposure, but also of adult and of child-directed TV exposure, with stronger correlations for child-directed TV viewing, which can have implications when interpreting the effects of this covariate.

Table 2. 6. Descriptive statistics, presented in Mean (SD) in hour/day, for media-diary estimates of total touchscreen time, total TV time, and total TV time split by adult-directed and child-directed TV viewing, for high and low touchscreen media users. User groups differ in total touchscreen use exposure.

	Low users (<15 min/day)	**High users (≥15 min/day)**	**Between-groups comparison**
At 12 months			
Total Touchscreen*	**0.71 (1.27)**	**1.91 (2.01)**	***p = 0.019***
Total TV	1.33 (1.62)	2.16 (2.14)	*n.s. (0.140)*
*TV Adult**	0.52 (1.03)	0.94 (1.41)	*n.s.(0.254)*
*TV Child**	0.81 (1.12)	1.06 (1.37)	*n.s. (0.484)*
At 18 months			
Total Touchscreen*	**0.78 (0.95)**	**2.19 (1.65)**	***p = 0.001***
*Total TV**	1.04 (1.15)	1.77 (1.77)	*n.s. (0.093)*
*TV Adult**	0.22 (0.52)	0.50 (0.81)	*n.s. (0.149)*
TV Child	0.83 (1.03)	1.31 (1.59)	*n.s. (0.211)*
At 3.5 years			
Total Touchscreen*	**0.58 (0.67)**	**1.98 (1.63)**	***p < 0.001***
*Total TV**	1.69 (2.02)	2.48 (1.58)	*n.s. (0.154)*
*TV Adult**	0.86 (1.41)	0.71 (0.78)	*n.s.(0.654)*
TV Child	0.69 (1.02)	1.58 (1.75)	*n.s. (0.062)*

** Values that exceed 3 standard deviations from the mean were trimmed (i.e. changed to be one more than the non-trimmed highest value)*

2.4. Overview of the TABLET lab-study assessments

At each of the three visits to the *Babylab* (12 months, 18 months, and 3.5 years), children took part in a battery of assessments, including experimental tasks and standardised optometric and developmental assessments. Paper-form parental-report questionnaire measures were also collected. See the complete battery in Table 2. 7, including eye-tracking, electrophysiological and observational data. In the section below, only the assessments that are relevant for this thesis will be discussed.

Table 2. 7. Complete task battery for the TABLET lab-visit at each age point.

	12 months	***18 months***	***3.5 years***
Parent-report online surveys			
Basic demographic variables including Mother's and Father's Education, Date of Birth, Gender, and Gestation	✓	-	-
Media use questionnaire	✓	✓	✓
Media diary	✓	✓	✓
Very-short-IBQ/very-short-ECBQ/short-CBQ	✓	✓	✓
Sleep	✓	✓	✓
Parent-report lab-based surveys			
Vineland-II Adaptive Behavior Scales	-	-	✓
CBCL	-	✓	✓
SDQ	-	-	✓
Eye-tracking based measures			
Gap-overlap Task (Block 1)	✓	✓	✓
Free-viewing of dynamic and static scenes (Block 1)	✓	✓	✓
Memory task (Block 1)	✓	✓	-
Anti-saccade Task (Block 2)	✓	✓	✓
Visual Search Task (Block 2)	-	✓	✓
Inhibition task (Block 2)	✓	-	-
Sequence learning task (Block 2)	-	✓	-
Lab-based measures			
Mullen Scales of Early Learning	✓	✓	*(VR Scale)*
Parent-child play	✓	✓	✓
EEG	✓	✓	-
Executive Function battery	-	-	✓
Visual function battery	-	-	✓
Lab-based physiological measures			
Activity	✓	✓	✓
Other: Heart Rate, GSR, Temperature	✓	-	✓

IBQ = Infant Behavior Questionnaire; ECBQ = Early Childhood Behavior Questionnaire; CBQ = Childhood Behavior Questionnaire; CBCL = Child Behavior Checklist; SDQ = Strengths and Difficulties Questionnaire; VR = Visual Reception

Measuring cognitive processes in infancy and toddlerhood is challenging for many obvious reasons. Firstly, young children have shorter attention spans than older children and adults so they do not stay still for enough number of repetitions of the same task (which is the standard in other fields of experimental psychology). Furthermore, because they have shorter periods of optimal performance due to changing emotional states and needs, long batteries of tasks are usually prone to some lost data, which often leads to developmental datasets having many missing data cases. Secondly, young participants do not yet completely understand verbal rules and they often do not follow instructed behaviours, much less so when instructions are given to overcome a prepotent response. To deal with these constraints, developmental scientists have ingeniously designed implicit experimental paradigms that are simple and child-friendly, making use of colourful and dynamic stimuli, game-like tasks, or tasks that replicate a child's everyday situation. Child-appropriate screen-based tasks tend to make use of simple stimuli (Richards, 2010) with sharp contrasts between the edge of objects and abrupt audio-visual changes, which are likely to tap into low-level visual abilities. This is an important consideration in the context of the main topic of this thesis, given that popular screen and touchscreen content also makes use of these audio-visual features (Taggart et al., 2019; Wass & Smith, 2015). Behavioural tasks using three-dimensional stimuli, rule-based performance (socially or internally imposed), and game-like contexts, are likely to prompt more higher-order cognitive processing (Choudhury & Gorman, 2000; Wass, 2014b) and also to be more ecological valid measures of everyday functioning, but again are difficult to successfully conduct with very young children.

Another strategy adopted by developmental scientists is the use of alternative measures of performance that do not require a motor or verbal response. Registering gaze patterns and looking behaviours using an eye-tracker device (which was previously achieved by video-coding), sometimes recurring to experimental paradigms that are based on learning contingencies between stimuli and responses (gaze-contingent), has been a favourite among these alternative tools (Gredebäck, Johnson, & Hofsten, 2009).

Eye-tracking assessments

Studying attention and oculomotor control in infancy and childhood has been critical to capture the child's view of the world – where they attend, what they miss – and to address their opportunities for learning and development (Aslin, 2007). In developmental science, eye-trackers have been traditionally used to simply study looking performance, most often in preferential looking paradigms (e.g. Klin, Lin, Gorrindo, Ramsay, & Jones, 2009), but relatively more recent studies made use of eye-tracking to address a wide range of scientific questions in the context of attentional processes, by employing techniques that allow for fine-grained spatiotemporal analyses (Falck-Ytter, Hofsten, Gillberg, & Fernell, 2013; Hessels, Niehorster, Kemner, & Hooge, 2016; Saez De Urabain, Johnson, & Smith, 2014).

Eye-tracking is an increasingly common method for studying visual attention and online cognitive processing. The most popular method to monitor and record the viewer's eye movements makes use of the light (glint) reflected from the eye cornea when near-infrared light is shone to the eye. The gaze position is estimated with high accuracy by identifying the relative position of this corneal reflection (which roughly remains fixed) to the pupil of the eye (which rotates with eye movement). Computer algorithms, based on video recordings of the pupil and the near-infrared light reflections collected by cameras placed in front of the observer, build a model relative to a 2D scene plane, such as a monitor where the stimulus is presented, and compute where the viewer's gaze is pointing to at every moment. By taking up advances in head-tracking algorithms or by making use of targets placed on the viewer's head, the model can include the distance from the viewer's eyes to the scene plane, making it possible to record eye movements in infants and young children without requiring head restraint – see Figure 2. 4. This substantially reduces the discomfort of infants and children and their willingness to participate (Gredebäck et al., 2009; T. J. Smith & Saez De Urabain, 2017).

In the TABLET project and present thesis results, infants' gaze coordinates were recorded at a rate of 120Hz using a Tobii TX-300 eye-tracker (Tobii Technology, Stockholm, Sweden). To record corneal reflection data the eye-tracker has an infrared light source and a camera mounted below a 23-inch flat-screen monitor (16:9, 1920X1080 pixels), where stimuli were presented. The Tobii system uses a head-tracking algorithm and measurements of gaze direction from each eye separately. The stimuli presentation and gaze recording were handled using MATLAB (version R2015a, MathWorks Inc., Natick, MA, USA) and the Psych Toolbox (version 3.0.12; Brainard, 1997) running on a MacBook Pro (Intel Core i7 CPU @ 2.5GHz, 16GB RAM, OS X 10.10.5) via the Tobii SDK. Scripts were implemented in the lab for these experiments. Children sat on their parent's lap 60 centimetres away from the screen. The distance and height of the screen were adjusted for each child to obtain good tracking of the eyes.

Before starting each experimental block, a five-point calibration sequence was run using a child-appropriate procedure (Senju & Csibra, 2008). After calibration, the protocol of tasks started. The researcher could skip trials manually if the child was not attentive, or play an attention grabber sound to engage the child again. Stimulus presentation continued until the end unless children became overly fussy and were unable to complete it.

The tasks within this thesis were implemented to automatically respond to online looking behaviour with the help of the eye-tracking system (gaze-contingent), permitting the study of eye movements in a truly interactive manner (Wass et al., 2011). In addition, attention-grabbing sounds and audio stimuli to keep the experiment engaging were played through stereo external speakers located at both sides of the presentation screen.

Parents were instructed to not intervene (as much as possible) and to direct their gaze away from the screen during the experiment. The session was monitored and recorded with a web camera located above the screen by using the ScreenFlow screen-casting software.

The full eye-tracking battery (~15-20 minutes) included two different blocks. In the first block, children were presented with free-viewing scenes (dynamic movies and static illustrations) and with a Gap-Overlap Task (see details in Chapter 4), followed by a memory task (presented only at 12 and 18 months). In the second block, which ran right after the first (unless the child needed a break) but required a recalibration, children were presented with an infant Anti-saccade task (see Chapter 4), followed by an infant Visual Search Task (presented only at 18 months and 3.5 years, see Chapter 3), and then an inhibition task (presented only at 12 months) and a sequence learning task (presented only at 18 months). Only the Gap-Overlap, the Anti-saccade, and the Visual Search Tasks were included in this thesis, in the interest of the thesis aims, in view of the background literature for each task, and considering preliminary data analysis.

Figure 2. 4. Illustration of a child on the eye-tracking lab set-up, doing the Anti-saccade Task (see Chapter 4).

Executive Function assessments at 3.5 years

During the first three years of life, EF assessment is severely restricted due to 1) the limitations that social demands, motor coordination, and language comprehension place on performance on conventional EF measures, and 2) an incomplete or not yet fully integrated EF structure (Fiske & Holmboe, 2019; Hendry et al., 2016). Although a collective of measures have been shown to drive and predict EF (including measures reported in this thesis under the attention control umbrella; Hendry et al., 2016), tasks that traditionally tax EF processes (updating, shifting, and inhibiting) require verbal instructions, rule-following, and complex responses (such as tapping buttons, or sorting cards), and some decision-making (choosing among different answers; Garon et al., 2008). Because of these constraints, EF was only measured in the TABLET sample at the 3.5 years visit, when EF measures can be administered. At this assessment, an approach was taken to measure EF across various tasks and contexts (e.g. on a touchscreen monitor mounted on a table, with 3D objects) to capture as much variance of behaviour as possible. This meant that multiple measures of EF (that differed in terms of data types) were collected. The battery of EF tasks was done sequentially in the same order for all children, right after the eye-tracking session. The EF session was done in a different room than the eye-tracking session, which had plenty of space for all activities. Parents were in the room but were put purposefully on the side of the room, filling questionnaires. The whole setup of the EF session and the procedure of the tasks are described in Chapter 5.

2.5. The TABLET analysis plans

2.5.1. Pre-registration of the visit at 3.5 years

There is a recent scientific focus on reproducible research (Open Science Collaboration, 2015), and this seems to be of particularly importance in fields shaping current policies. To contribute to the movement the 3.5 years longitudinal visit was pre-registered on the Open Science Framework (Spies, 2013). The hypotheses, the study design and the data processing steps and analyses used to test the hypotheses can be found at the pre-registration page[5]. Data processing steps can also be found there. On each empirical chapter of this thesis the specific pre-registered hypotheses and analysis plans will be introduced and discussed when differing from the current analysis.

2.5.2. Longitudinal data analysis

Longitudinal studies collect repeated observations on one or more variables at successive time points, making it possible to examine both inter- and intra-individual change in development processes. Because this allows the examination of the ordering of correlations over time an inference about the direction of effects studied can be proposed, although causality cannot be established. However, longitudinal data presents methodological challenges from an analysis point of view, e.g. missing data due to attrition from the study.

[5] *https://osf.io/fxu7y*

Generalized Estimation Equation (GEE)

In Chapter 3 and 4, attention control measures derived from the eye-tracking data were investigated across visits in the context of touchscreen media use. A Generalized Estimation Equation (GEE) model approach (Pickles, 1998) was used in these studies because it accounts for some of the limitations associated with using standard repeated measures analysis of variance (ANOVA) for longitudinal developmental datasets. Firstly, the GEE is able to account for missing data, avoiding the reduction of sample size that comes from listwise deletion on any instance of missing data (which happens with other repeated-measures methods; Muth et al., 2015). Missing data is also a common problem in developmental eye-tracking (Wass, Forssman, & Leppänen, 2014). Secondly, the GEE allows for non-normally distributed data, which is a common situation with modest sample sizes. In the studies presented in the next chapters, linear GEE models, with an identity link and unstructured correlation matrix, were estimated. Wald tests were used to determine the significance of effects, calculated from the sandwich estimator of the parameter covariance matrix.

Structural Equation Modelling (SEM)

For the EF assessment, multiple measures were used to capture the different EF processes and children's behaviour in different contexts. This is a strong approach that enables the study of the specific EF processes related to touchscreen media use. To understand the associations among EF observed variables (and thus take into consideration the underlying EF structure at this age), and the association between touchscreen media use and EF constructs (latent variables), a Structural Equation Modelling (SEM) framework was used. SEM is a type of multivariate data analysis that accommodates the use of continuous and categorical indicators (which was the case for the TABLET EF dataset). The SEM modelling method involves estimating the parameters in the model, and assessing the model 'goodness of fit', either in reference to the absolute fit of the model or the relative fit of different models. In this thesis, only absolute fit statistics measures were computed to confirm how similar the model (EF structure) generated data were to the observed data. It is generally agreed that SEM requires large sample sizes (ideally more than 100 participants; Bijleveld & van der Kamp, 1998) and that having a small sample can affect the reliability of the parameter estimates. When this is the case, simpler models (with fewer parameters) are preferred. Given these limitations and the TABLET modest sample size, the SEM analysis in this thesis is severely restricted to the testing of the main model, and findings should be treated with caution.

2.6. Summary of Chapter 2

- Chapter 2 provided an overview of the TABLET project and the methodological and statistical approaches taken to address the aims of this thesis.
- There are important strengths as well as limitations associated with a quasi-experimental longitudinal design.
- The TABLET sample media use and background variables at each longitudinal visit were described, as well as the touchscren user groups (high and low users of touchscreen devices).
- Parent-report estimates of (touch)screen time are associated with media-diary time measures.
- Parent-report estimates of Background TV (how much the television is on in the home) is related to both adult- and child-directed TV viewing (as measured by media-diary measures).
- Unlike more basic analysis methods, using a GEE or SEM modelling approach enables some of the challenges associated with developmental longitudinal data, such as missing data and varied distributional properties between variables, to be accounted for in the analysis.

Chapter 3:

Parallel visual search is faster in toddlers with high touchscreen use

3.

3.1. Introduction

Family ownership of touchscreen devices (e.g., smartphones, tablets and touchscreen computers) increased rapidly in recent years, with 32% of pre-schoolers using a mobile phone in 2018 and 58% using a tablet device (increasing from 20% and 28% respectively in 2013; Ofcom, 2019), and the TABLET project (see Chapter 2) survey showing daily usage as young as 6 months of age (Bedford et al., 2016). How such devices impact a child's developing brain is a pressing question of concern to parents, paediatricians, scientists and early-years practitioners. Official guidelines from national agencies, for example the American Academy for Pediatrics (AAP Council on Communications and Media, 2016) and the UK Chief Medical Officers (Davies, Atherton, Calderwood, & McBride, 2019), and international bodies (World Health Organization, 2019) advise parents to avoid screen time for infants and toddlers, i.e. younger than 18 months (AAP Council on Communications and Media, 2016), and limit/curate screen time for older children. However, given the prevalence of touchscreens in the home environment (Ofcom, 2019; Rideout, 2017) and the increasing use of touchscreens to entertain, pacify and educate toddlers (Ahearne et al., 2016; Bedford et al., 2016) it seems these guidelines are not being followed. Touchscreen technologies provide and attractive source of stimulation, and enable very early interactive use at an age when attentional control mechanisms are undergoing rapid development.

The popular media is awash with claims that touchscreen exposure is creating a generation with increasing behavioural and cognitive problems (S. Greenfield, 2015; Sigman, 2012) including ADHD-like behaviours (Carr, 2011). In particular, it has been hypothesised that exposure to fast-paced "unnatural" levels of sensory stimulation at an age of peak neurocognitive development may influence the development of attentional control (Christakis, 2016; Rothbart & Posner, 2015). However, there is no clear empirical evidence linking toddler touchscreen use with developing attentional problems. In this chapter, I present the first study investigating the longitudinal association between toddler and child touchscreen use and the development of attention control.

Touchscreen devices are pervasive in today's family environment but their relatively recent introduction means that research on their impacts on development is severely limited. Instead, parallels with more established studies of related digital media such as television (similar to touchscreen video viewing) and videogames (similar to interactive app use) offer a theoretical background for formulating hypothesis (see a detailed argument for this approach in Chapter 1). Empirical evidence from television suggests that excessive screen time may be associated with attentional problems (Christakis et al., 2004). Action video-gaming has been shown to increase performance on cognitive tests including enhanced visual processing, attentional and motor control in adults (Green & Bavelier, 2008), and older children (Trick et al., 2005). By placing the screen in the hands of a very young child, when neural plasticity is at its peak (Amso & Scerif, 2015; Werchan & Amso, 2017), touchscreen devices are potentially amplifying these positive and negative effects.

Evidence that excessive television viewing has a small but significant longitudinal association with attention problems across childhood (Nikkelen et al., 2014) has been attributed to a recalibration of how individuals control their attention. Experience of having their attention and arousal state guided externally by the TV's rapidly changing, non-contingent flow of sensory information, has been hypothesised to lead to difficulties in voluntarily focusing and sustaining attention on cognitive demanding tasks, such as schoolwork, that do not provide an external drive (Christakis, 2009) – see 'Modern digital content: trigger of orienting responses' subsection in Chapter 1. On the other hand, video-gaming contingent and highly dynamic and complex sensory environments, have been proposed to be optimal for training or exercising rapid and deliberate deployment and shifting of attention (Hubert-Wallander, Green, Sugarman, & Bavelier, 2010) – see Chapter 1 section 1.4 'The case of action video-gaming'.

The dissociation between automatic stimulus-driven attention (*exogenous*) and voluntarily, internally-driven attention (*endogenous*) is key to understanding how individuals balance the distribution of their cognitive resources in everyday experiences. Traditionally this dissociation in visual selection has been investigated using visual search paradigms that can contrast these two modes of control (Treisman & Gelade, 1980; Wolfe, 1998). Participants are usually instructed to search for a target in an array of distractors by either a single visual feature (e.g. colour; *singleton or single search*) or by multiple features (e.g. colour and shape; *conjunction search*).

Single search taps into exogenously-driven attention since target selection occurs in *parallel* across the visual field due to its unique features 'popping out' (Wolfe, Cave, & Franzel, 1989). As such, single search is fast and efficient, and the time taken to locate the salient target (reaction time; RT) should not increase as the number of homogeneous distractors increases – i.e. set size is irrelevant. In contrast, conjunction search demands an endogenously-driven attentional process (more effortful and inefficient) as it requires distractors to be serially examined and dismissed, and as such, as the number of multi-feature distractors increase, so does the RT to find the target (Wolfe, 2000). Visual search is especially useful for identifying individual differences in developing attention control in pre-/non-verbal infants and toddlers, as the search task can be made gaze-contingent via an eye-tracker, ensuring stimuli is presented only when the child is attending to it. The contingent learning provided by the gaze-contingency environment can train young children to associate reward (pleasing sounds and animations) with the target without the need for instruction (Kaldy et al., 2011).

Prior reports of associations between screen time and ADHD-traits/attention control problems are often based on parent, teacher or pediatrician observational assessments (Christakis et al., 2004; Kostyrka-Allchorne, Cooper, & Simpson, 2017a; Nikkelen et al., 2014). To begin understanding the developmental neuroscience mechanisms that may give rise to such cognitive changes, studies need to use paradigms (e.g. gaze-contingent visual search) that can identify which aspects of attentional control (e.g. serial or parallel selection; exogenous or endogenous attention) differ based on screen use. There are no studies looking at visual search in high TV users. However, studies of adults and children with ADHD-traits (reported to be higher in high-TV users; Christakis et al., 2004), have reported impaired endogenous-control (i.e. conjunction search) but intact exogenous attention (i.e. single feature search; Mullane & Klein, 2008). Exposure to fast-paced and/or fantastical television in pre-school children has also been shown to immediately impair executive function (Lillard, Li, & Boguszewski, 2015b), which, as described in Chapter 1, relates to endogenous control of attention. Such physically passive screen exposure involves highly systematic and stimulus-driven viewing behaviour (Mital et al., 2010; T. J. Smith, Mital, & Dekker, n.d.) that may be accentuated in kids' TV (Taggart et al., 2019; Wass & Smith, 2015), displacing opportunities for training endogenous control. However, evidence from adult video-gamers has shown the opposite effect: faster conjunction by expert action video-gamers compared to matched non-videogame players (Castel et al., 2005; Green & Bavelier, 2003). These results have been interpreted as a greater flexibility in how endogenous attention is deployed that cannot simply be explained by speeded motor responses trained through the frequent motor demands of video-gaming (Hubert-Wallander et al., 2010).

The current study

Touchscreen use, in toddlers (Bedford et al., 2016; Cristia & Seidl, 2015), may simultaneously involve both the saliency-guided viewing mode similar to television (e.g. during video viewing) and the physically and cognitively interactive demands of video-gaming, e.g. during games and educational app use. At 18-months-of-age, touchscreen use has switched from a predominantly non-interactive mode of use (e.g. YouTube controlled by a parent) to a mixture of endogenously-controlled video selection and app use involving more complex screen scrolling and touch gestures (Bedford et al., 2016; Cristia & Seidl, 2015; Kabali et al., 2015). This moment-by-moment profile of use, its demand on user attention, and the sense of agency provided by a mobile touchscreen device, distinguishes the experience on such devices from either television viewing or videogaming. By being exposed to such varied and artificial demands on attention, toddlers with high daily touchscreen use may exhibit a different profile of attention control to toddlers with lower touchscreen experience. To investigate these differences in attention control for the first time, the present study compared visual search performance between children who have high daily touchscreen use (HU) to matched low daily touchscreen-use children (LU), both at 18-months and at 3.5-years. Specifically, I predicted differences in endogenous attention (i.e. conjunction search) in HUs compared to LUs, given that prior literature (Barr et al., 2010; Bavelier et al., 2012; Christakis et al., 2004; Green & Bavelier, 2003; Kirkorian et al., 2009; Nikkelen et al., 2014), generally attributed effects to this domain of control. Toddlers were assessed on visual search arrays of varying sizes (5, 9, or 13 objects) in single-feature search trials (e.g. a red apple amongst blue apples; i.e. *parallel* selection) and conjunction trials (i.e. a target red apple among slices of red apples and full blue apples; i.e. *serial* search).

3.2. Method

3.2.1. Participants

As described in Chapter 2, the current study forms part of a battery of studies administered to infants as part of the *TABLET* study. In the current chapter, attention control abilities were profiled via a lab-based gaze-contingent visual search task at the 18-month and 3.5-year visits. At the 18-months visit only 43 toddlers (out of 49 who came to the visit; 22 high-users and 21 low-users) completed the Visual Search Task and were included. At the 3.5-years visit only 43 children (out of 46 children; 25 high-users and 18 low-users) completed the task and were included in the analysis.

3.2.2. Touchscreen media use assessment and usage groups

As described in Chapter 2, parents reported on their infants' media use via an online questionnaire, at 12 months, 18 months, and 3.5 years before visiting the *Babylab,* by answering the questions: 'On a typical day, how long does your child spend using a touchscreen device (tablet, smartphone or touchscreen laptop)?' (see Chapter 2 for more details). Children were coded as high or low users of touchscreen devices at each visit, based on their place in relation to the total sample median cut-off at each age point: < median "low users" (LU), > median "high users" (HU). Median use at 18 months and at 3.5 years was 15 minutes/ day.

At recruitment, groups were matched on background variables: mothers' education (below degree vs. degree level or above), general development level (Mullen Early Learning Composite score), concurrent age (days), gender and concurrent background TV Viewing (in minutes per day, assessed through parent-report on the online media questionnaire by asking the question: 'On a typical day, how long is a TV switched on in your home?'). At 18 months and 3.5 years, groups were not matched in terms of Background TV (see Chapter 2). When considering only the participants who were included in the analysis for this chapter, these figures were broadly replicated, except for the difference between groups on Background TV at 18 months which was marginally significant for the current chapter sample. See Table 3. 1 and Table 3. 2 for detailed descriptive statistics of each visit usage group and background measures, for the sample who contributed with data on the Visual Search Task. For continuous numerical variables data is presented as Mean (Standard Deviation) and difference between user groups was tested with an independent samples t-test. For categorical variables data is presented as N (Proportion) and difference between user groups was tested with a Pearson Chi-Square.

Table 3. 1. Descriptive and frequency statistics for high and low touchscreen media users at 18 months.

18 months visit	**Low users (<15 min/day)**	**High users (≥15 min/day)**	**Between-groups comparison**
N	**21**	**22**	
Touchscreen use (min/day)	**2 (3)**	**40 (34)**	***p* < 0.001**
Gender			
Girls	11	7	n.s. (0.172)
Boys	10	15	
Mother's Education			
School leaving or college	1	0	n.s. (0.311)
University or postgrad	20	21	
Missing, N/A		1	
Age (days)	536 (20)	545 (22)	n.s. (0.178)
Background TV (mind/day)	97 (115)	166 (116)	n.s. (0.059)
MSEL Standard Score	114 (17)	109 (18)	n.s. (0.344)

Table 3. 2. Descriptive and frequency statistics for high and low touchscreen media users that were included in the analysis of the Visual Search Task at 3.5 years. User groups differ in background TV (High users parents' reported more background TV).

3.5 years visit	**Low users (<15 min/day)**	**High users (≥15 min/day)**	**Between-groups comparison**
N	**18**	**25**	
Touchscreen use (min/day)	**3 (4)**	**64 (76)**	***p* = 0.001**
Gender			
Girls	11	9	n.s. (0.103)
Boys	7	16	
Mother's Education			
School leaving or college	0	3	n.s. (0.120)
University or postgrad	18	21	
Missing, N/A		1	
Age (days)	1259 (13)	1256 (19)	n.s. (0.642)
Background TV (min/day)	**116 (150)**	**205 (122)**	***p* = 0.042**
MSEL Visual Reception	63 (9)	67 (10)	n.s. (0.142)

Given that Background TV was generally significantly different between usage groups at 18 months and 3.5 years, and this is a potential variable of interest to the study considering that is a proxy of the whole family media environment, it was included as a covariate in follow-up analyses, with any significant main effect retained and reported in appendixes.

3.2.3. Stimuli and procedure: the Visual Search Task

How the session was monitored, the participants' gaze coordinates calibrated and recorded, and the stimuli presentation handled, is described in Chapter 2.

The Visual Search Task was presented only at the 18 months and 3.5 years visit, after a battery of other tasks, including the Gap-Overlap Task and the Anti-saccade Task presented in Chapter 4, making use of an eye-tracking system attached to a screen and a stimuli presentation gaze-contingent protocol. The task was adapted from Kaldy and colleagues (Kaldy et al., 2011) by project collaborators (Dr. Luke Mason and Dr. Celeste Cheung). It was adapted so that it made use of the original task timings and visual stimuli and sizes, but so that it was experimenter-independent and gaze-contingent to automatically control the pacing of the trials and identify target detection. In each trial, participants were presented with a search array for 4 seconds or until they fixated the target (a red apple) – see Figure 3. 1. The arrays were either a single feature array – e.g. a target red apple among blue apples, or a conjunction array – a target red apple among segments of red apples and blue apples. Before each trial, the target red apple 'flew' into the centre of the screen to attract participants' attention, direct their gaze to the centre of the screen, and to emphasize the special status of the target. Once the participant fixated this central attention getter, it disappeared and the search array was presented. At the end of the trial, the target item spun clockwise 360 degrees, then counter clockwise other 360 degrees, to provide a reward animation and promote active search. The red and blue apple-shaped items subtended 4.36x4.36 degrees of visual angle, the elongated apple items subtended 1.07x6.36 degrees, and all items were constrained to appear within a virtual circle with a diameter of 25.54 degrees. The positions of target and distractors were randomized from trial to trial. As the target apple 'flew in' before each trial, an airplane sound effect played; while the search array was presented, a ticking clock sound effect played; and during the spinning animation reward after trial ended, a clapping sound effect played.

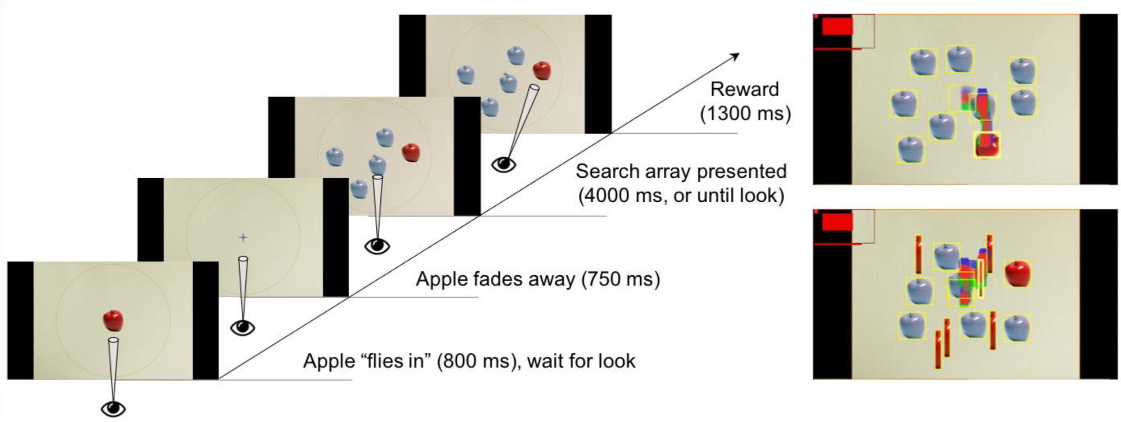

Figure 3. 1. On the left, stimulus sequence for experimental trials in the Visual Search task (stimuli drawn to scale). On the right, examples of a single search display for set size 9 (top) and of a conjunction search display for set size 13 (bottom), with defined areas of interest relevant to gaze-contingency and performance measures (not visible to participants).

Although trial presentation was continuous, trials were grouped in blocks: Block 1: 3 single feature trials (trial order was fixed with set size 5-9-5); Block 2: 10 trials (trial order was randomised with 1 single feature, set size 9, and 9 feature conjunction trials, set size 5, 9 or 13); Block 3: 13 trials (trial order was randomised with 4 single feature, set size 5 and 9, and 9 conjunction trials, set size 5, 9 or 13), see Table 3. 3.

Table 3. 3. Visual Search task experimental trial search array at 18 months.

Set size	**Single**	**Conjunctive**	**Total**
5	4	6	10
9	4	6	10
13	0	6	6
Total	8	18	26

Alterations to procedure at the visit at 3.5 years

At 3.5 years, 31 participants (20 HUs) were presented with three extra practice single trials (trial order was fixed with set size 5-9-5) at the beginning of the task, which were followed by instructions to search for the apple. This was due to the need for an explicit task goal at this age group and to avoid children engaging in distracting behaviours during performance (e.g. counting the number of items on the screen). After instructions, trial sequence was carried as reported above (see Table 3. 4 for the number of trials in each search type and set size). For the other 12 participants (5 HUs) whose data was collected before the need for this practice block was identified, the task was presented as it was reported above (total of 26 trials). Within-participants analysis with task block (block pre-instructions, total of 3 single trials, and main block, total of 26 trials; N = 31) and between-participants comparison analysis with task procedure (children who were presented with 26-trials procedure with no instructions, and children who were presented with 29-trials procedure with instructions; N = 43) did not reveal any significant effects on single search outcome measures – see Appendix 3a. Therefore, for further analysis all participants at 3.5-years visit, and all trials that each participant was presented with, were included.

Table 3. 4. Visual Search Task experimental trial search array at 3.5 years.

Set size	Single	Conjunctive	Total
5	6	6	12
9	5	6	11
13	0	6	6
Total	11	18	29

3.2.4. Analytic approach

Outcome measures

Behavioural data was exported at the end of the session. For each trial, information about whether the participant had fixated the target during the trial (*success*) and the time from the presentation of the array until gaze was on the target AOI (i.e. area of interest), if the target was fixated before the end of the trial (*Search Reaction Time, SRT*) were computed. Offline, raw gaze data was processed to automatically exclude trials based on gaze quality and latency duration logical flags. First, all trials were segmented and pre-processed to exclude gaze offscreen, interpolate data and average eyes. Within each trial, gaze was extracted from the moment the array was presented to the event marker where gaze entered the target Area of Interest (or trial ended). Trial exclusion criteria were: (i) skipped trial; (ii) proportion of missing gaze samples out of the entire trial length less than 25%; (iii) maximum gap of missing data less than 500 ms; (iv) SRT to find the target higher than 200 ms. See processing steps in Appendix 3b or Appendix 3 in the pre-registered OSF page[6]. Only valid trials were considered to calculate proportion of success (accuracy) and mean SRT for each search type and set size combination (5 in total).

Data from 4 children were not collected at the 18-month visit and from 2 children at the 3.5-year visit due to technical problems or excessive fussiness or fatigue. Additionally, 2 children at the 18-month visit (2 HU) and 1 child at the 3.5-years (HU) visit were excluded because they did not have enough number of valid trials on the task (number of valid trials were either 0 or 1). See Table 3. 5 for the number of valid trials and participants in each usage group.

Table 3. 5. Task related number of participants and number of valid trials, represented in terms of N, Mean number of valid trials (Standard Deviation), by age visit and concurrent touchscreen media usage group. Significance values were assessed on an independent samples t-test.

Number of valid trials	Low users N, Mean (SD)	High users N, Mean (SD)	Between-groups comparison
At 18 months	21, 22.0 (3.5)	22, 22.6 (4.7)	n.s. (p = 0.643)
At 3.5 years	18, 22.4 (5.1)	25, 21.2 (5.7)	n.s. (p = 0.484)

Statistical analysis

As described in Chapter 2, the data analysis plan for the 3.5-year visit was pre-registered on the Open Science Framework along with analysis steps[7]. Although it was proposed the effects in SRTs in the Visual Search Task would be tested in a repeated-measures ANOVA, in the current chapter effects were tested using a Generalised Estimating Equation (GEE) model – this was because a GEE model allowed us to include more data points than a repeated-measures ANOVA and so to include less compliant participants. See Appendix 3c for the pre-registered ANOVA analysis results, which were broadly similar to the ones reported below.

First, the association between current touchscreen user group and Visual Search Task performance was analysed separately for each age visit. Linear GEE models, with an identity link and unstructured correlation matrix, were run to predict 1) accuracy and 2) SRTs, using search type (single, conjunction), set size (5, 9), and the concurrent visit usage group (LUs and HUs) as predictors. Main effects models were run first and interaction effects were added in a second step. A separate GEE model was then run for the conjunction search including the additional set size 13 trials. Due to changes of

[6] https://osf.io/xptua/
[7] https://osf.io/fxu7y

touchscreen user group membership (i.e. HU and LU) between visits, concurrent GEE models were followed by longitudinal regressions with continuous daily touchscreen exposure at concurrent and previous visits.

GEE Models for which Background TV minutes (covariate unmatched between groups) had a significant main effect on the dependent variable were reported in Appendixes.

3.3. Results

3.3.1. Accuracy: Success at finding the target

To make sure biases in success rates did not confound effects on search reaction times, the proportion of ‘successful’ trials i.e., those in which the participant fixated the search target (the red apple) before the end of the trial (4-seconds) was analysed first.

Visit at 18 months

A GEE model including concurrent user group (HU, LU) at 18 months, search type (single, conjunction) and set size (5, 9; 13 was omitted due to absence in single trials) as predictors of visual search accuracy (see Table 3. 6) showed, as expected, a significant main effect of search type, with more accurate scores in the single (mean = 94%) compared to conjunction search (mean = 88%). There were no usage group or set size main effects or interactions.

Following Kaldy and colleagues (Kaldy et al., 2011), for the conjunction search there were additional trials with set size 13 (to limit the number of trials these were not included in the single search because no set size effect was expected). When a GEE model was run including the trials with set size 13 as predictors of conjunction search accuracy, there was an overall main effect of set size, and Bonferroni corrected pairwise comparisons showed significantly better accuracies in the set size 5 (mean = 89%, p = 0.001) and 9 (mean = 87%, p = 0.001) compared with 13 (mean = 74%), but no significant difference between the first two (p > 1). There were no Group effects or interactions.

Visit at 3.5 years

Similar results to those at 18 months were found on a GEE model including concurrent user group (HU, LU), search type (single, conjunction) and set size (5, 9) as predictors of visual search accuracy at 3.5 years (see Table 3. 6). Again, there was a significant main effect of search type, with more accurate scores in the single (mean = 98%) compared to conjunction search (mean = 88%). There were no other significant main or interaction effects. When including the trials with set size 13 in the GEE model there were no main or interaction effects.

Table 3. 6. Summary statistics of GEE models including concurrent usage group, search type and set size as predictors of accuracy in the Visual Search Task. The final sample at 18-months included 21 LUs and 22 HUs; the final sample at 3.5 years included 18 LUs and 25 HUs.

Search Accuracy GEEs	**18 months** Wald χ^2 (df), *p* value	**3.5 years** Wald χ^2 (df), *p* value
Main model		
Search Type	**6.488 (1), p = 0.011**	**12.694 (1), p < 0.001**
Set Size (5, 9)	1.261 (1), p = 0.261	0.097 (1), p = 0.755
Group	1.522 (1), p = 0.217	0.19 (1), p = 0.663
Type**Group*	0.043 (1), p = 0.836	0.299 (1), p = 0.585
Set size**Group*	0.902 (1), p = 0.342	0.159 (1), p = 0.690
Type*Set size	0.051 (1), p = 0.821	2.507 (1), p = 0.113
Type*Set size**Group*	1.922 (1), p = 0.166	0.126 (1), p = 0.722
Follow-up model restricted to conjunction search with set size 13		
Set Size (5, 9, 13)	**15.599 (2), p < 0.001**	0.022 (2), p = 0.989
Group	0.252 (1), p = 0.615	0.226 (1), p = 0.634
Set size**Group*	3.841 (2), p = 0.147	3.15 (2), p = 0.207

Concurrent Background TV minutes was not significantly related to accuracy at any visit so it was not included as covariate in supplementary analysis.

3.3.2. Search Reaction Time to find the target

Visit at 18 months

A GEE model including user group (HU, LU), search type (single, conjunction) and set size (5, 9) as predictors of visual search reaction time at 18 months (see Table 3. 7 for full statistics) showed a significant main effect of search type, with faster reaction times in the single (mean = 1145ms) compared to conjunction search (mean = 1451ms).

The model also showed a main effect of user group, and an interaction between group and search type. Given that the 3-way interaction between group, search type, and set size was marginally significant, two separate GEE models were run for each search type. These showed that reaction times were significantly faster in the HUs (mean = 1037ms) compared to the LUs (mean = 1252ms) only during single search, but groups did not differ in the conjunction search (HU mean = 1463ms, LU mean = 1438ms) – see Figure 3. 2.

Table 3. 7. Summary statistics of GEE models including concurrent usage group, search type and set size as predictors of reaction time to find the target in the Visual Search Task at 18 months. The final sample included 21 LUs and 22 HUs.

Search Reaction Time GEEs	**18 months** Wald χ^2 (df), *p* value
Main model	
Search Type	**27.621 (1), p < 0.001**
Set Size	3.665 (1), p = 0.056
Group	**11.353 (1), p = 0.001**
*Group**Type	**6.626 (1), p = 0.010**
*Group**Set Size	0.088 (1), p = 0.767
Type*Set Size	**10.822 (1), p = 0.001**
*Group**Type*Set Size	2.991 (1), p = 0.084
Follow-up model restricted to single search	
Set Size (5, 9)	2.656 (1), p = 0.103
Group	**6.401 (1), p = 0.011**
*Group**Set Size	1.716 (1), p = 0.190
Follow-up model restricted to conjunction search	
Set Size (5, 9)	**8.651 (1), p = 0.003**
Group	0.034 (1), p = 0.853
*Group**Set Size	0.998 (1), p = 0.318
Follow-up model restricted to conjunction with set size 13	
Set Size (5, 9, 13)	**14.406 (2), p = 0.001**
Group	0.006 (1), p = 0.938
*Group**Set Size	1.163 (2), p = 0.559

Additionally, there was a marginally significant effect of set size, and a set size by type interaction in the main model. The GEE models split by search type showed significantly faster search in set size 5 (mean = 1351ms) compared to set size 9 (mean = 1554ms) only for the conjunction search. For single search, there were no significant differences between set size 5 (mean = 1206ms) and 9 (mean = 1084ms). There were no significant group by set size interaction effect in either search type.

A separate GEE for the conjunction search, which included set size 13, showed an overall main effect of set size, with Bonferroni corrected pairwise comparisons showing significantly faster reaction times in set size 5 compared to 9 (p = 0.009) and 13 (mean = 1631ms; p = 0.007), but no significant difference between set size 9 and 13 (p > 1). There was no main effect of Group or interaction between Group and set Size.

See descriptive statistics (mean and standard deviations) across search types, set size, age visits, and touchscreen use group in Appendix 3d.

Concurrent Background TV minutes was not significantly related to SRTs in the main model or the follow-up models, so it was not included as covariate in supplementary analysis.

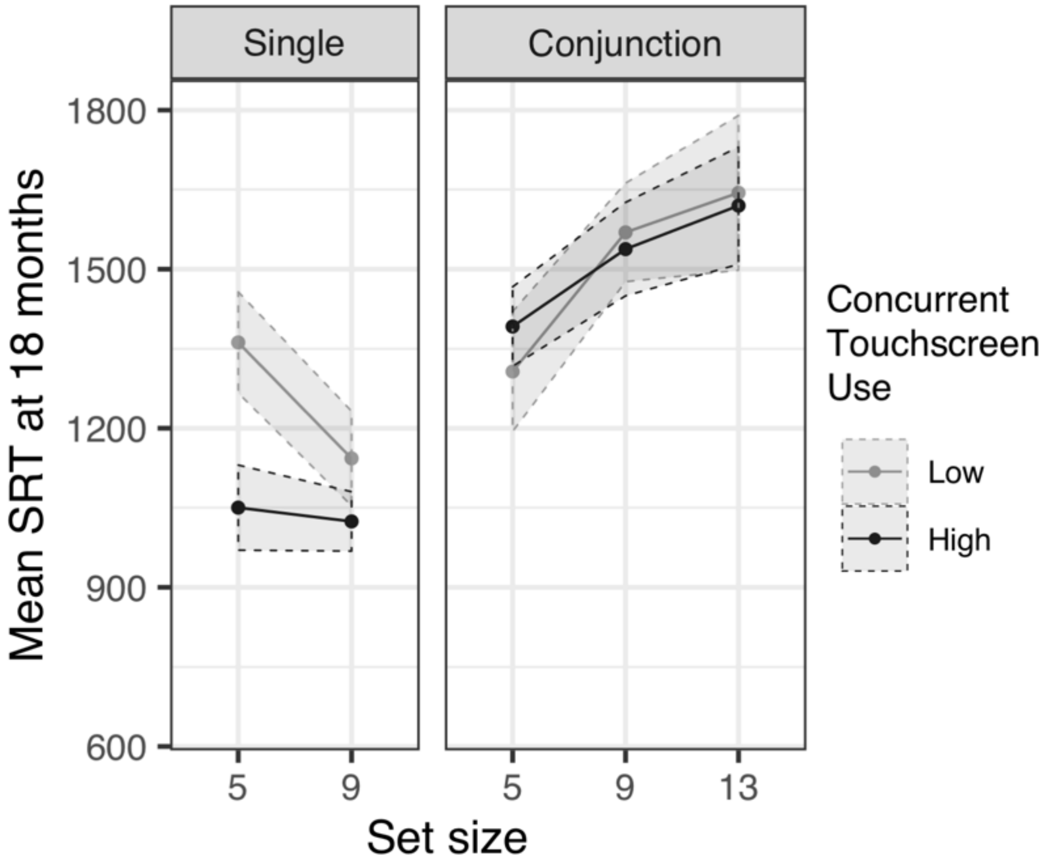

Figure 3. 2. Mean Search Reaction Time (ms) for each touchscreen use group (LU=grey lines, HU=black lines) at 18 months (N = 43) as a function of search type and set size in the Visual Search Task. Shaded areas represent standard error of the mean.

To investigate if faster single search in HUs was due to faster learning of the target-reward relationship within the task, a post-hoc exploratory analysis was ran split by task block, testing differences between single search RT from the first three trials (Block 1: 3 single trials) with the single search RT on all other trials (Block 2 and 3: 5 single trials) – see Figure 3. 3. This analysis showed that HUs (Block 1 mean = 1054ms) were faster than the LUs (mean = 1389ms) in Block 1, t(40) = 2.357, uncorrected p = 0.023, Bonferroni corrected p = 0.046; while LUs' single search got quicker over the course of the task (Block 2 and 3 mean = 1141ms) to resemble the HUs (mean = 1020ms,) – final single feature trials, no significant group difference, t(40) = 1.067, uncorrected p = 0.292, Bonferroni corrected p = 0.584.

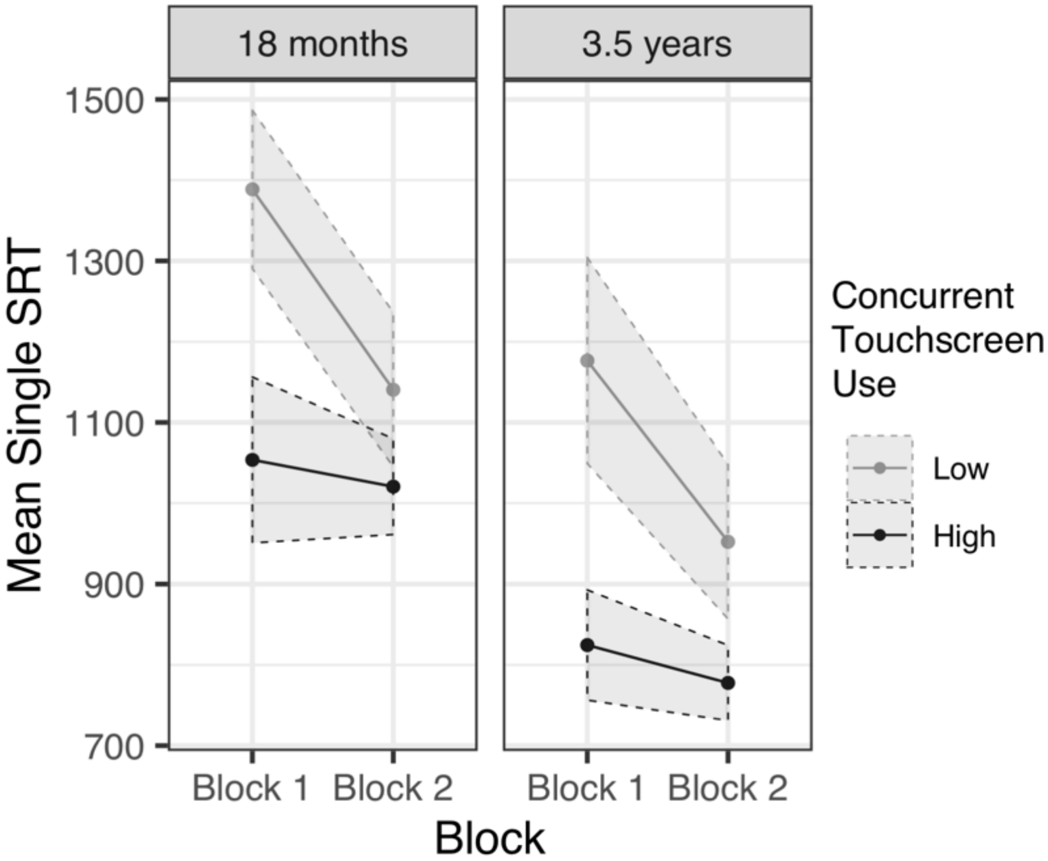

Figure 3. 3. Mean Search Reaction Time (ms) in Single-feature search trials for each concurrent touchscreen use group (LU=grey lines, HU=black lines) at 18 months (left panel) and 3.5 years (right panel) as a function of experiment block. Shaded areas represent standard error of the mean.

Visit at 3.5 years

As for results at 18 months, a GEE model including user group (HU, LU), search type (single, conjunction) and set size (5, 9) as predictors of visual search reaction time at 3.5 years (see Table 3. 8 for full statistics) showed a significant main effect of search type, with faster reaction times in the single (mean = 897ms) compared to conjunction search (mean = 1355ms).

In terms of user group, there was no main effect or search type by group interaction, although the trends were in the same direction as at 18-months (see Table 3. 8). Given the *a priori* prediction of differing usage group effects within each search type from 18-months, this was tested in two GEE models split by search type. SRTs were significantly faster in the HUs (mean = 802ms) compared to the LUs (mean = 1029ms) only during single search, in line with the previous results – see Figure 3. 4. There were no user group differences for conjunction search.

Table 3. 8. Summary statistics of GEE models including concurrent usage group, search type and set size as predictors of reaction time to find the target in the Visual Search Task at 3.5 years. The final sample at 3.5 years included 18 LUs and 25 HUs.

Search Reaction Time GEEs	**3.5 years** Wald χ^2 (df), p value
Main model	
Search Type	**53.597 (1), p < 0.001**
Set Size	0.077 (1), p = 0.781
Group	2.173 (1), p = 0.140
***Group**Type**	2.62 (1), p = 0.106
***Group**Set Size**	0.027 (1), p = 0.869
Type*Set Size	0.228 (1), p = 0.633
***Group**Type*Set Size**	1.78 (1), p = 0.182
Follow-up model restricted to single search	
Set Size (5, 9)	0.555 (1), p = 0.456
Group	**5.454 (1), p = 0.020**
*Group**Set Size	1.909 (1), p = 0.167
Follow-up model restricted to conjunction search	
Set Size (5, 9)	0.119 (1), p = 0.730
Group	0.066 (1), p = 0.798
*Group**Set Size	0.443 (1), p = 0.506
Follow-up model restricted to conjunction with set size 13	
Set Size (5, 9, 13)	**5.994 (2), p = 0.050**
Group	0.327 (1), p = 0.567
*Group**Set Size	2.058 (2), p = 0.357

In terms of set size, there was no main effect or the predicted interaction with search type. Given the *a priori* expectation that there should be a set size effect in the conjunction but not the single search, the effects were broken down by running GEE models split by search type for set sizes 5 and 9. For single search, there was no significant effect of set size. Within conjunction search there was also no significant set size effect. However, when a separate GEE for this search type which included set size 13 was ran, a significant effect of set size was found. Bonferroni corrected pairwise comparisons showed no significant difference in reaction times between set size 5 (mean = 1336ms) and 9 (mean = 1375ms), p > 1, or between 9 and 13 (mean = 1539ms), p = 0.273. The effect between set sizes 5 and 13 was marginally significant (p = 0.072).

See descriptive statistics (mean and standard deviations) across search types, set size, age visits, and touchscreen use group in Appendix 3d.

Concurrent Background TV minutes was not significantly related to SRTs in the main model or the single search follow-up model; but it was related to SRT in the conjunction search follow-up models. When including parent-reported Background TV minutes at 3.5 years in these models, results remained similar, with the set size main effect marginally significant. See these results in Appendix 3e.

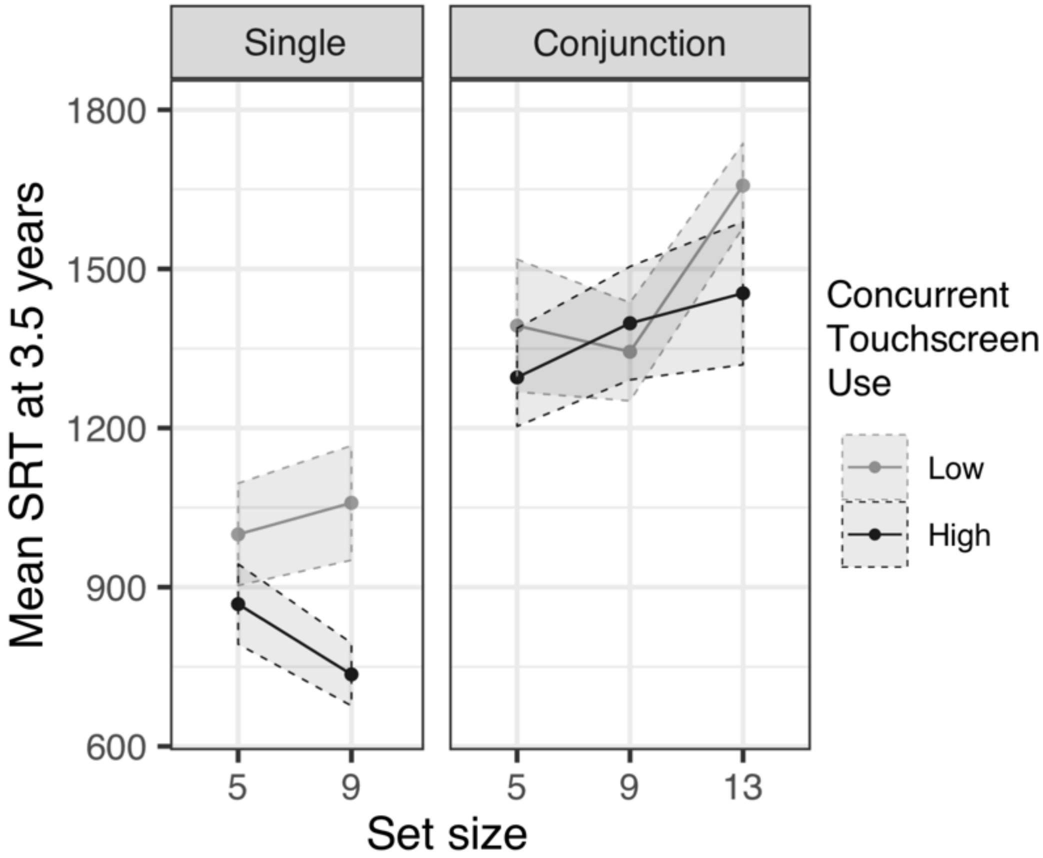

Figure 3. 4. Mean Search Reaction Time (ms) for each touchscreen use group (LU=grey lines, HU=black lines)at 3.5 years (N = 43) as a function of search type and set size in the Visual Search Task. Shaded areas represent standard error of the mean.

To investigate if, again, these effects were dependent on the time course of the task, a post-hoc analysis was ran split by task block, comparing single search RT from the first three trials (Block 1) with the single search RT on all other trials (Block 2 and 3) – see Figure 3. 4. As for the 18-months results, this analysis showed that HUs (mean = 825ms) were significantly faster than LUs (1177ms) on the first three trials – t(26.55) = 2.434, uncorrected p = 0.022, Bonferroni corrected p = 0.044; while LUs' reaction times (mean = 952ms) decrease over the course of the task to a similar level as the HUs (mean = 778ms) – final single feature trials, no significant group difference, t(25.059) = 1.643, uncorrected p = 0.113, Bonferroni corrected p = 0.226.

Longitudinal analysis

Given that daily reported touchscreen use, and so group membership, varied along the longitudinal visits (see Chapter 2 'Touchscreen Media Use: Group coding'), the last aim of this chapter was to test whether the effects on single search RT were specific to continuous concurrent reported touchscreen use, or whether there were longitudinal associations with earlier visits touchscreen duration.

At 18 months, a linear regression model with daily parent-reported touchscreen minutes at the concurrent (18 months) and previous (12 months) age point as a predictor of reaction time in the single search condition showed that duration of concurrent use was significantly associated with single search reaction time (standardized beta coefficient = -0.615, p = 0.032), *over and above earlier usage*, with no association for 12-month touchscreen usage duration (standardized beta coefficient = 0.476, p = 0.093).

In line with this result, at 3.5 years, a linear regression model which included reported touchscreen minutes at the concurrent (3.5 years) and previous (12 and 18 months) age points, showed that duration of concurrent use was marginally associated with single search reaction time (standardized beta coefficient = -0.350, p = 0.050), with no association for usage at either 12 months (standardized beta coefficient = 0.176, p = 0.65) or 18 months (standardized beta coefficient = -0.019, p = 0.962).

3.4. Discussion

The results of this chapter show for the first time that toddlers with above average daily touchscreen use orient faster to a salient visual search target than low-users. This parallel search advantage is present at 18 months and at 3.5 years (while a main or interaction effect was not present, follow-up analyses showed an effect of group on single SRT) without concomitant differences in serial (i.e. conjunction) search performance. These results are specific to the child's concurrent touchscreen usage, not past usage, and may be due to a pre-existing advantage (a bias towards saliency) coming into the task, rather than within-task learning of the rewarding nature of the apple target, as low users performance did not differ from the high users by the end of the task.

Overall these results indicate that high users of touchscreens were faster in finding a "pop-out" target (i.e. exogenous orienting of attention) but performed similarly to low users in serial search (endogenous orienting of attention).

The shorter latency to orient to the target specifically in the single feature trials could suggest that high users are more saliency driven, at least when saliency is predictive of task-relevant or rewarding content. Various developmental mechanisms may explain the salience-bias demonstrated by HUs. Repeated recent exposure to the intense audio-visual screen content of touchscreen devices that is designed to guide attention towards reward may have 1) trained the HUs to have a greater precision in their saliency filtering (see Chapter 1 subsection 1.4.4. 'Pathway of influence: learning to learn'), and/or 2) lead to increased expectation that salient stimuli are relevant and rewarding (see Chapter 1 subsection 1.3.2 ‘Modern digital content: trigger of orienting responses’); both of which benefit performance while doing searching for the ‘pop-out’ red apple on the single arrays.

Related evidence for how viewer’s environment and prior experiences can alter, immediate and long-term, attentional biases is provided by demonstrations of attentional capture and history-driven attention (B. A. Anderson et al., 2011; Theeuwes, 2019). In light of this research, the faster bias towards the salient target during single search conditions can be seen as a result of prior experience of reward for such salient features (common in touchscreen interfaces) or priming of low-level visual processing for features related to the apple target. Both of these mechanisms can be considered learning of statistical regularities of the viewer’s visual environment based on reinforcement learning through constant reward following attention allocation to certain features over others. Such reinforcement may happen at a faster rate and for stronger saliency-response pairings via experience with a digital touchscreen than in the real-world due to the design and content of the platform and their contingency on user interaction.

Toddler-directed digital content uses visual salience to trigger faster reflexive saccades (Calvert, Huston, Watkins, & Wright, 1982) that aid comprehension and simplify the information extraction task for young viewers (Calvert et al., 1982; Wass & Smith, 2015) and guide viewer attention (Frank et al., 2012; Kirkorian et al., 2012; T. J. Smith, 2012), by making high points of saliency and contrast often predictive of the location of interesting, informative and rewarding stimuli, such as a speaking character’s face (Wass & Smith, 2015). Touchscreen interface design (Carr, 2011) borrows and intensifies these principles, making use of elements of the interface that are to be interacted with or that are intended to deliver feedback, e.g. a successfully completed goal, to stand out from their surroundings using salient visual events such as high contrast, colour changes or motion (Dix, Finlay, Abowd, & Beale, 2004). This stimulus-response-reward associations on touchscreen content might be seen as a formal feature of interactive media, and by demanding a physical contingent action to such salient content, the stimulus-response-reward associative connections may be strengthened (D. R. Anderson & Davidson, 2019) and prime salience processing. Through brain plasticity and synaptic pruning, bottom-up networks, which are more consistently used, become more efficient, accompanied by an increase in speed of processing and sensitivity to frequently encountered stimuli features (e.g. perceptual narrowing; Sorcinelli & Vouloumanos, 2018).

In the context of digital child-directed content, a viewing behaviour that privileges quick orienting to salient features might be suitable. Equipped with this behaviour, acquired through daily exposure to such visual stimuli and priors, high users start the current task ready to successfully select the popping-out target, without having to learn the target-reward pairings. This behaviour does not confer benefits on conjunction search because this type of search requires serial processing, and performance does not benefit from bottom-up stimuli features. Low users, who do not have such experience, are slower at the beginning of the task, but seem to learn this association during the task itself and catch up with high users at the end of it.

It is important to note that this saliency bias seen in high users, which benefited their performance on visual single search, could potentially compromise performance in tasks that require deliberate control over attention away from salient features. Similar evidence of a saliency bias has been reported by studies using machine learning to discriminate children with ADHD from neurotypical children based on the features (i.e. dynamic visual saliency features including texture processing, edge colour contrast, and oriented edges) of the visual scene their gaze is directed towards whilst free-viewing TV (Tseng et al., 2012). It has been proposed that ADHD individuals' attention may be more stimulus-driven due to weakened ability to inhibit unwanted saccades and endogenously control attention (Munoz et al., 2003). The role that reward and learned value (B. A. Anderson et al., 2011) play in developing this saliency bias needs to be investigated in future studies as it is currently unclear whether salient features are intrinsically more rewarding to high users or whether high users have altered reward processing, as has been observed in ADHD individuals (Tripp & Wickens, 2009).

While visual search is a suitable approach to dissociate serial from parallel attention allocation, the current paradigm does not require the participant to resolve a conflict between saliency and task relevancy: there is no need to suppress response to bottom-up features in order to achieve the task goal. Such conflicts occur frequently in a toddler's everyday environment and overcoming them may be critical for their learning and socio-cognitive development, for example when learning the names of objects from a caregiver in the presence of distracting toys, people or screens. Prior studies of individuals with ADHD (Mullane & Klein, 2008; Munoz et al., 2003) and of the immediate impact of fast-paced and/or fantastical television (which makes use of salient features; Taggart et al., 2019) on pre-school children (Lillard, Li, & Boguszewski, 2015b) have reported impairments specifically for the endogenous attention control required to resolve such conflicts (i.e. inhibitory control). Future studies should evaluate the extent to which the attention allocation behaviour seen in high users replicates when exogenous and endogenous orienting are in conflict, situations which require the more traditional components of endogenous attentional control which may still show impairment in this population (as they have previously been shown impaired for ADHD and extensive TV viewers). The hypothesis would be that an increased capture by bottom-up features would lead to a failure to engage top-down control of attention (Christakis et al., 2004; Singer, 1980; Zimmerman & Christakis, 2007).

Overall, these results are not showing an impairment or enhancement in top-down attention control, and do not match prior evidence of endogenous impairments from television viewing (Barr et al., 2010; Christakis et al., 2004; Kirkorian et al., 2009; Nikkelen et al., 2014) or enhancements through action video games playing (Bavelier et al., 2012; Green & Bavelier, 2003). This highlights the differential effects that each type of media platform used by young children might have on their developing mind. Touchscreen devices offer a multiplicity of types and modes of use (e.g. passive and active video viewing, cognitive and motor-demanding games, social interactions via videocalls) as well as content varying widely in sensory-cognitive demands and age-appropriateness (e.g. on YouTube), which may have differential impacts on viewer attentional control. Future studies examining precise measures of attentional control using appropriately powered samples, as has been shown for fine-motor development (Bedford et al., 2016) and language (Linebarger & Walker, 2005), should investigate the differential associations with such variation in touchscreen use. Alternatively, it is possible that the design specifications of the Visual Search task were not sensitive enough to elicit or reveal serial processing attention detriments in high users.

In the present study, the single search advantage is an isolated independent effect of the general use of touchscreen devices, and not associated with household background TV duration. This may be because this advantage is gained through the interactivity with the touchscreen (D. R. Anderson & Davidson, 2019). Alternatively, this may be because parent-report Background TV does not accurately capture the specific time spent watching television by the child (Orben & Przybylski, 2019), neither the time the child spent watching child-directed TV (but see in Chapter 2 Table 2. 5 the association with child-directed TV watching). Future studies should attempt to use objective tracking of screen media use, including child-directed TV viewing, along with context and content of touchscreen exposure, in order to gain a more precise insight into variants of use. However, given the multiple screens a toddler may be exposed to on a daily basis (e.g. a shared tablet, their parent's smartphone, communal TV) and the inability of an objective tracking application knowing *who* is watching the screen, such objective measurement is not easy to accomplish with this population.

Alternatively, it could be that high users were faster due to being more familiar with screen-based activities and/or more engaged with the screen, thus more aroused and alert for optimal performance. However, if that was the case, one would think that they should have also shown quicker search times on the conjunction search, better accuracy, and/or increased number of valid trials (compliance to the task), but such a benefit in performance was not observed. It also does not seem to be the case that these results reflect a general speeded processing of visual information, which has been reported by several studies with adult and younger video-game players (e.g. Castel et al., 2005; Dye, Green, & Bavelier, 2009a; 2009b), given that performance on conjunction search did not benefit from this speed advance.

Given that these findings are based on associations it is important to consider directionality of effects. It is possible that children who are biased towards highly salient content are both more likely to use screens and be faster at parallel visual search, rather than the touchscreen use *causing* faster saliency filtering. Whilst causality cannot be addressed with this observational design, the lack of longitudinal associations between touchscreen time and single search performance, and the change of children from user groups across visits, support the hypothesis that repeated experience with a touchscreen dynamically strengthen bottom-up processes. However, future studies, specifically intervention studies (i.e. randomized controlled trials) that can control for pre-existing differences in usage groups, are critical to demonstrate the causality of the immediate touchscreen exposure effect on the visual attention behaviour reported in this study.

This study has shown that high users have an altered attentional profile, in a context where saliency on the screen is parallel to task relevancy. It is important then for future studies to address 1) the role that reward and learned value (B. A. Anderson et al., 2011) play in developing this attention allocation pattern by establishing conditions for which the salience is non-predictive of reward; 2) the specificity of this attention behaviour to screen contexts by assessing if this pattern can be replicated in other contexts of visual attention such as real world scenarios.

In conclusion, this study has shown faster saliency driven attention in a visual search task in high touchscreen users at 18 months and 3.5 years, but no concomitant difficulties in serial, top-down, search. Increased experience of highly salient and rewarding stimuli on touchscreens may prepare high users to initially respond faster to these types of features when on a screen. The effects were driven by current, rather than past touchscreen usage. Future studies are required to replicate these findings, establish a direct causal influence of touchscreen use on the neurodevelopment of attention control and assess whether effects are moderated by the media platform, content and context of use.

3.5. Summary of Chapter 3

- This chapter reported on associations between concurrent toddler touchscreen use and attention control.
- Attention control was distinguished in terms of parallel (exogenous) and serial (endogenous) selection on a gaze-contingent Visual Search Task.
- The time it took for children to find the search target (a red apple) in the varying search array types (single, i.e. a red apple amongst blue apples, and conjunction, i.e. a red apple amongst blue apples and red apple slices) and set sizes (5, 9, 13) were the dependent measure.
- Search latencies were slower in conjunction search compared to single search; set size was only relevant in conjunction search.
- It was found that high and low users of touchscreens did not differ in accuracy or search latencies in conjunction-feature trials (i.e. *serial* search, or top-down control of attention).
- It was found that high users were faster than low users on single-feature trials (i.e. *parallel* selection, or 'pop-out' search), suggesting that high users may be more bottom-up driven.
- The effect on single search was driven by current, rather than past touchscreen usage, suggesting a dynamic remapping of stimulus saliency and response association.
- The effect on single search was independent of Background TV, highlighting the potentially unique role of these devices for the developing mind.
- Increased recent experience of highly salient, rewarding, and physically contingent stimuli may prepare high users to respond faster to these types of features when on a screen.
- While high users' saliency bias benefited their performance on this Visual Search task, it is crucial to establish if this behaviour generalizes to tasks where saliency is not synonymous with task relevancy, and whether it compromises the ability to resolve a conflict between both processes, in contexts that demand attention to be suppressed from bottom-up features in order to achieve the task goal.

Chapter 4:

High touchscreen use across the first 3.5 years of life is associated with faster bottom-up attention and concomitant reduced top-down attention

4.

4.1. Introduction

Early in life, individual differences in attention control are thought to underpin executive function (Hendry et al., 2016) and self-regulation (Posner et al., 2012; Rothbart, Sheese, Rueda, & Posner, 2011). Attention control has a pivotal role in information processing by filtering the potential information available from the environment based on what is relevant to a specific task or state in time. This selection results from the interaction between two processes: *exogenous* (stimulus-driven and automatic, e.g. looking at a briefly flashed cue) and *endogenous* (goal-driven and voluntary, e.g. disengaging attention from an object to look to a novel one) attention (Colombo & Cheatham, 2006; Connor, Egeth, & Yantis, 2004; Sarter, Givens, & Bruno, 2001) – see further discussion in Chapter 1 sub-section 1.1.1. These can be studied by measuring performance in saccadic paradigms, which have been used to investigate the neural substrates of attention in typical (Hood & Atkinson, 1993; Johnson et al., 1991; Scerif et al., 2006) and atypical (Amso & Scerif, 2015; Elsabbagh et al., 2013) development. Although under strong genetic control, the development of attention is thought to be subject to environmental influences (Posner, Rothbart, & Voelker, 2016). As it has been described in Chapter 1, one factor that investigators have hypothesized to influence attention development is the visual experience of screen media activity [e.g. watching television (Nikkelen et al., 2014) or playing games (Dye & Bavelier, 2010; Rothbart & Posner, 2015; Rueda et al., 2005)].

Screen media activity is a common form of entertainment for children (see usage figures in Chapter 1 section 1.2). Touchscren devices share similarities to a television, in terms of its formal (auditory and visual) features; and to a video-game console, in terms of the interactivity and contingency. High levels of television exposure have been proposed as a risk factor for ADHD like behaviours (S. Cheng et al., 2010; Christakis et al., 2004; Martin et al., 2012; Nikkelen et al., 2014) and executive function problems (Barr et al., 2010; Kostyrka-Allchorne, Cooper, Gossmann, Barber, & Simpson, 2017c; Nathanson et al., 2014). Lang and colleagues have shown that television's formal features elicit automatic attention shifts which can overload cognitive processing resources (Lang, Kurita, Gao, & Rubenking, 2013; Lang, Zhou, Schwartz, Bolls, & Potter, 2010). Children orient to these formal features (Calvert et al., 1982), but importantly, these orienting responses were suggested to disrupt children's attention during and after television viewing (Geist & Gibson, 2000; Kirkorian et al., 2009; Kostyrka-Allchorne, Cooper, Gossmann, Barber, & Simpson, 2017c; Schmidt et al., 2008). Others have shown that excessive television formal features have an immediate negative impact on executive performance (Lillard & Peterson, 2011; Lillard, Drell, Richey, Boguszewski, & Smith, 2015a). Researchers suggested that, by eliciting orienting responses, television content overly activates bottom-up processes and depletes executive resources needed for subsequent performance (Lillard, Li, & Boguszewski, 2015b) – see discussion of this hypothesis in Chapter 1 subsection 'Modern digital content: trigger of orienting responses'.

In constrast, there has been consistent evidence for a potential facilitation effect of playing AVGs on the training of attention skills. Studies comparing participants with different frequencies of playing AVG and intervention studies have showed enhanced perceptual abilities (i.e. basic vision, processing speed, endogenous control) from video-gamers (Bavelier et al., 2012; Dye, Green, & Bavelier, 2009a; Hubert-Wallander, Green, & Bavelier, 2011a, Green & Bavelier, 2003; Trick et al., 2005). While playing AVGs seems to train visual attention, the specific levels of processing at which this occurs require further investigations (Hubert-Wallander, Green, & Bavelier, 2011a): generally researchers have often attributed the evidence of changed exogenous attention by AVG experience to endogenous aspects of attention (Bavelier et al., 2012; Hubert-Wallander, Green, & Bavelier, 2011a).

The study presented in the previous chapter, using the same dataset used within this chapter (the TABLET Project dataset, described in Chapter 2), showed that toddlers with high touchscreen use were faster in exogenous visual search – i.e. detecting a red apple amongst blue apples; while no differences between users were found for endogenous search – i.e. finding a red apple amongst blue apples and red apple slices (see Chapter 3). While these findings indicate that attention in toddlers with high touchscreen use was faster in pop-out search, it could be that either 1) high users are more saliency-driven than low users or 2) high users are faster at learning the task requirements and therefore pre-set their saliency bias in response to the reward. Importantly, during the visual search task, looking at the most salient object was never detrimental to the task end goal and it could not be assessed whether faster orienting to saliency compromised performance on goal-directed behaviour like, for example, ignoring distractors. Thus, the current study aims to clarify this later hypothesis by testing whether a saliency bias in high touchsreen users is still found when it is detrimental to the viewing task, and to further investigate the associations between endogenous attention and touchscreen use in this context.

The current study

The purpose of the current study was to examine whether the duration of touchscreen use during early childhood changes performance on attention control. It makes use of two tasks suitable for investigating the interplay of exogenous and endogenous influences on saccadic control in infants and toddlers. The *Gap-Overlap task* assesses the disengagement (endogenous) and facilitation (exogenous control) of attention by measuring the latency of moving the eyes from a central stimulus to a peripheral one (Atkinson, Hood, Wattam-Bell, & Braddick, 1992; Elsabbagh et al., 2009; Farroni, Simion, Umiltà, & Barba, 1999; Hood & Atkinson, 1993; Johnson et al., 1991) in three increasing levels of visual competition. In “overlap” trials (higher level of visual competition condition), the central and the peripheral stimulus overlap in time and this competition disrupts otherwise automatic saccades (Fischer, Gezeck, & Hartnegg, 1997; Cousijn, Hessels, Van der Stigchel, & Kemner, 2017), requiring additional oculomotor and cognitive processes to actively disengage which produces relatively longer latencies. In “gap” trials (least competitive condition), a temporal offset between the disappearance of the central stimulus and the onset of the peripheral one provides a spatially nonspecific warning signal, which triggers alertness and *facilitates* fixation release (Jin & Reeves, 2009; Klein & Foerster, 2001; Reuter-Lorenz, Hughes, & Fendrich, 1991) leading to faster latencies. The *Anti-saccade task* indexes the *endogenous* process of inhibiting automatic attention shifts by measuring if a participant can suppress a saccade to a cue (pro-saccade) to make a saccade in the opposite direction. Traditionally, the anti-saccade paradigm makes use of verbal instructions to test adult participants’ abilities to inhibit a saccade to the cue (Guitton, Buchtel, & Douglas, 1985; Munoz & Everling, 2004). In the infant implementation of the task, infants are motivated to look at the opposite location of a cue by presenting another stimulus there after a delay (target) and reinforcing such response with an animated stimulus (reward). Over the course of the task, infants learn to inhibit the response to the cue (Johnson, 1995) to respond more quickly to the target and anticipate its appearance (anti-saccade). The reflexive pro-saccades to the cue reflect exogenous processing, whereas the voluntary anti-saccades to the target reflect endogenous processing (Amso & Scerif, 2015; Scerif et al., 2006).

As discussed above (and in detail in Chapter 1), screen media literature has shown associations between endogenous attention and early exposure to television viewing (reduced performance indexed by questionnaire-based measures of attention problems; S. Cheng et al., 2010; Christakis et al., 2004; Nikkelen et al., 2014; and by executive function lab-based measures; Barr et al., 2010; Lillard & Peterson, 2011; Lillard, Drell, Richey, Boguszewski, & Smith, 2015a; Lillard, Li, & Boguszewski, 2015b; Nathanson et al., 2014) and AVGs (greater performance in lab-based measures of attention control; Dye, Green, & Bavelier, 2009a; Green & Bavelier, 2003; Hubert-Wallander, Green, & Bavelier, 2011a). Therefore I hypothesised that children with high touchscreen use would demonstrate different levels of endogenous control, which included the disengagement effect and the number and latency of anti-saccades and corrective looks, compared to the low users. In terms of exogenous attention, previous screen media literature did not suggest different levels of performance. However, in the study presented in the previous chapter, the high touchscreen users group showed faster pop-out search. To follow-up on this finding, this chapter tested whether evidence of faster exogenous responding (the facilitation effect, latency on the baseline condition, and latency of pro-saccades) was also present in the high user group in comparison to the low user group.

4.2. Method

4.3.1. Participants

The current study forms part of a battery of studies administered to infants as part of the TABLET study (please refer to Chapter 2 for details). Participants took part in a battery of experimental measures, including the saccadic control tasks described below, by visiting the *Babylab* as part of three longitudinal visits at 12 months (N = 53), 18 months (N = 49), and 3.5 years (N = 46).

4.3.2. Touchscreen media use and longitudinal stable usage groups

As described in Chapter 2, to assess touchscreen usage parents reported on their infants' media use, at the three visits, by answering the question: 'On a typical day, how long does your child spend using a touchscreen device (tablet, smartphone or touchscreen laptop)?' through an online questionnaire before visiting the *Babylab* (see Chapter 2 for details). Children were coded as high or low users of touchscreen devices at each visit, based on their place in relation to the total sample median cut-off at each age point: less than the median "low users" , greater than or equal to the median "high users". Median use at 12 months was 10 minutes/ day, and at 18 months and 3.5 years was 15 minutes/ day.

For some children, touchscreen usage was not consistent throughout the study and they changed their group membership between visits. The current chapter analysis comprises two tasks that participants did at all time points of the project, and a specific aim was to analysed the performance longitudinally, which required a touchscreen usage group variable that indexed children's touchscreen use across visits. For this reason, the current chapter only included participants that had a stable usage over time. To be considered for a stable usage group the child's group at either 12 months or 18 months would need to match the usage group at 3.5 years (e.g. if at 12-months a child was a low user and at 3.5 years he/she was also a low user, then he/she would be considered a stable low user; if at 12 and 18 months a child was a high user but at 3.5 years he/she was a low user, then he/she would be considered an unstable user and hence dropped from the longitudinal analysis). If children missed the last visit, they were included in a group if their usage was consistent on the other time points (this happened for 2 children who only missed the last visit but they were placed on the high usage group on previous visits, and for 3 high usage infants who only came to the first visit). See Appendix 4a for the possible group permutations and outcome longitudinal group classification. In total 14 children were low (stable) users (LUs), 26 were high (stable) users (HUs) and 13 children were considered unstable users (their usage across age points could not be described).

Covariates

Table 4. 1 presents detailed descriptive statistics for each longitudinal usage group, including touchscreen media use frequency and background measures: gender (0 = boy, 1 = girl), age (days) at each visit to the *Babylab*, Mothers' education (0 = below degree; 1 = university or postgraduate degree), general development level at 12 months (MSEL Standard Score), and average Background TV Viewing (min/day). To make sure that stable usage groups matched in these background variables independent samples t-tests were run for continuous variables and pearson chi-squared tests for binary variables. In follow-up analyses, variables which were not matched across groups (significance value below 0.05), were tested as covariates, with any that had a significant main effect retained in the analysis and reported in appendixes.

Table 4. 1. Descriptive and frequency statistics for key background variables by longitudinal touchscreen media user group. For continuous numerical variables data is presented as Mean (Standard Deviation); for categorical variables data is presented as N (Proportion) and difference between user groups (high and low users) was tested with a Pearson Chi-Square. High and low user groups differ in gender (high users group has a higher proportion of boys) and average Background TV (high users parents' reported more background TV).

Longitudinal stable grouping	**Low users**	**High users**	***Unstable***	**Between-groups comparison**
N	**14**	**26**	***13***	
Touchscreen Use				
Average Min/Day	3 (5)	54 (78)	*22 (20)*	**p = 0.003**
Gender				
Girls	9 (64%)	7 (27%)	*7 (54%)*	**p = 0.021**
Boys	5 (36%)	19 (73%)	*6 (46%)*	
Mother's Education				
School-leaving, college	0	3 (11%)	*1 (8%)*	*n.s. (p = 0.2)*
University, Postgrad	14 (100%)	22 (85%)	*12 (92%)*	
Missing/ N/A	0	1 (4%)	*0*	
Age				
At 12-months	378 (16)	375 (21)	*377 (23)*	*n.s. (p = 0.7)*
At 18-months	542 (18)	540 (16)	*540 (31)*	*n.s. (p = 0.7)*
At 3.5-years	1253 (13)	1257 (20)	*1260 (13)*	*n.s. (p = 0.5)*
Background TV				
*At 12-months**	127 (178)	230 (174)	*137 (138)*	*n.s. (p* = 0.084)
*Average**	118 (169)	236 (171)	*135 (121)*	**p = 0.042**
MSEL Standard Score				
At 18-months	111 (11)	108 (11)	*107 (12)*	*n.s. (p = 0.4)*

** One value that exceed 3 standard deviations from the mean was trimmed (i.e. changed to be one more than the non-trimmed highest value)*

4.3.3. Stimuli and procedure: saccadic control measures

The session procedure and how participants' eye coordinates were calibrated and monitored, and the stimuli presentation handled, is described in Chapter 2. The tasks below were presented at 12 months, 18 months, and 3.5 years, within a battery of other screen-based tasks, and made use of an eye-tracking system and a gaze-contingent stimuli presentation protocol.

The Gap-Overlap task

This task was presented within a block of tasks comprising dynamic and static scenes, and it was implemented by a project collaborator (Dr. Irati R. Saez de Urabain; Saez De Urabain, Nuthmann, Johnson, & Smith, 2017). It was experimenter-independent and gaze-contingent to automatically control the pacing of the trials.

All trials in this task began with a centrally presented animation – see Figure 4. 1. The animation, subtending around 6.5 degrees × 6.4 degrees, expanded and contracted to attract the child to the centre of the screen before the onset of the trial. The central stimulus and the background colour changed every block of 12 trials. After a delay of 200 ms once the child fixated the central stimulus (CS) a peripheral target was presented randomly to either left or right side of the screen, at the eccentricity of 18.5 degrees. The peripheral stimulus (PS) was always the same (a cloud) subtending about 6 degrees × 6 degrees. For 25% of trials, the PS was presented either on top or bottom of CS to avoid anticipation. The PS remained displayed until the child looked at it or until 4 seconds elapsed, after which the trial was skipped. When the child looked to the PS a novel animated audio-visual stimuli (reward) replaced it and the next trial started. Depending on the exact moment the CS disappeared and the PS appeared on the screen, the trials were flagged as Overlap, Baseline or Gap. In the Overlap condition, the PS appeared while the CS remained displayed so that the two stimuli overlapped until the end of the trial; in the Baseline condition, the CS disappeared and the PS appeared simultaneously; in the Gap condition, the CS disappeared and was followed by a gap of 200 ms before the PS appeared.

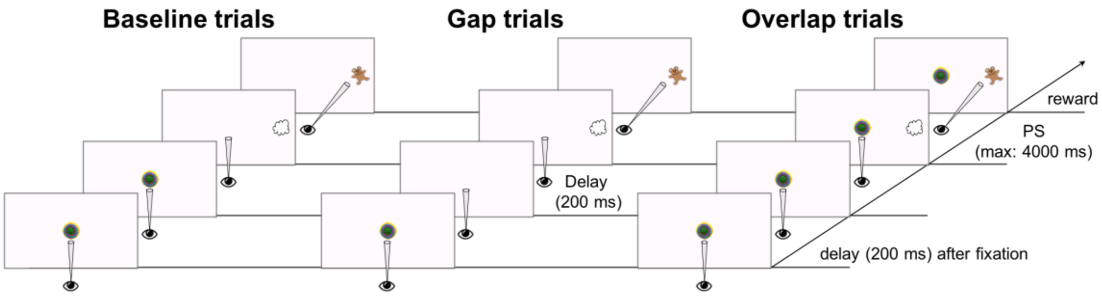

Figure 4. 1. Stimulus sequence for experimental trials in the Gap-Overlap Task. Stimuli drawn to scale. Every trial started with the central stimulus onset and were followed by the presentation of the peripheral stimuli (PS).

The three conditions were presented pseudo-randomly across seven blocks which were interleaved with other tasks of the study; a maximum of 70 trials (ignoring the vertical trials) was presented. Forty per cent of these trials were Overlap trials, thirty per cent were Baseline trials and another thirty per cent were Gap trials.

Saccadic latencies (ms) were defined as the time from the PS presentation onset to the first look to the PS and were extracted offline. All trials were automatically validated based on gaze quality flags and latency duration. See processing details in Appendix 4b or in Appendix 3 in the pre-registered OSF page[8]. Only valid trials were considered for average measures. Average latency was calculated for each condition. Disengagement was then calculated by subtracting the baseline latency from the overlap latency, and facilitation by subtracting the baseline latency from the gap latency.

[8] https://osf.io/xptua/

Data from 1 child at the 3.5-year visit was not collected due to technical problems.

For the analysis reported in this chapter, forty children (16 girls) who took part in the task were included – 26 HUs and 14 LUs based on longitudinal parent-report at all visits attended. Groups did not differ on the number of valid trials they yielded ($p > 0.05$). See Table 4. 2 for the number of valid trials and participants in each usage group.

The Anti-saccade task

This task was presented within a block of tasks administered after the block with the Gap-overlap Task and the dynamic and static scenes. It was implemented by a project collaborator (Dr. Luke Mason). It was experimenter-independent and gaze-contingent to automatically control the pacing of the trials and the timing of target and reward presentation.

All trials started with the presentation of a central stimulus (a star, subtending around 3 degrees × 3 degrees) which expanded and contracted to attract the child to the centre of the screen before the onset of the trial – see Figure 4. 2. When the participant looked to the central fixation stimulus, a distractor stimulus (a black circle, subtending 3 degrees × 3 degrees with 17 degrees to the right or left of the screen) appeared for 200 ms. After 1000 ms a target stimulus (a red circle, subtending 4 degrees × 4 degrees with 17 degrees eccentricity) was presented on the opposite side. When the child looked to the target an attractive animation of an animal with sound replaced it and the next trial started. If the participant looked at the target side before its presentation, the animation started immediately. For each participant, the Distractor and Target did not change sides across trials but side was balanced across participant groups. The task was presented in one continuous series of trials, consisting of 26 (at the 12 months visit) or 15 (at the 18 months and 3.5 years visits) trials. A subsequent block presenting distractor and target on the opposite side (rule switch block) was run but not considered for the current study.

Looks and reaction times towards stimuli were measured offline. In each trial it was identified whether the participant looked at the peripheral distractor stimulus and whether he/she looked at the peripheral target stimulus location before (or shortly after, up to 100 ms post-target onset, as in other studies using anti-saccade paradigms in infants; Scerif et al., 2006; and adults; Guitton et al., 1985) the onset of the target (look to target location before target presentation = anticipatory look). All trials were automatically validated based on gaze quality flags. See processing details in Appendix 4c or in Appendix 3 in the pre-registered OSF page[9]). If during a trial the child did not look to the distractor nor

[9] *https://osf.io/xptua/*

the target location before target appearance the trial was excluded on the basis that the child only responded reflexively to the target and failed to orient to the distractor. Only valid trials were considered for average measures.

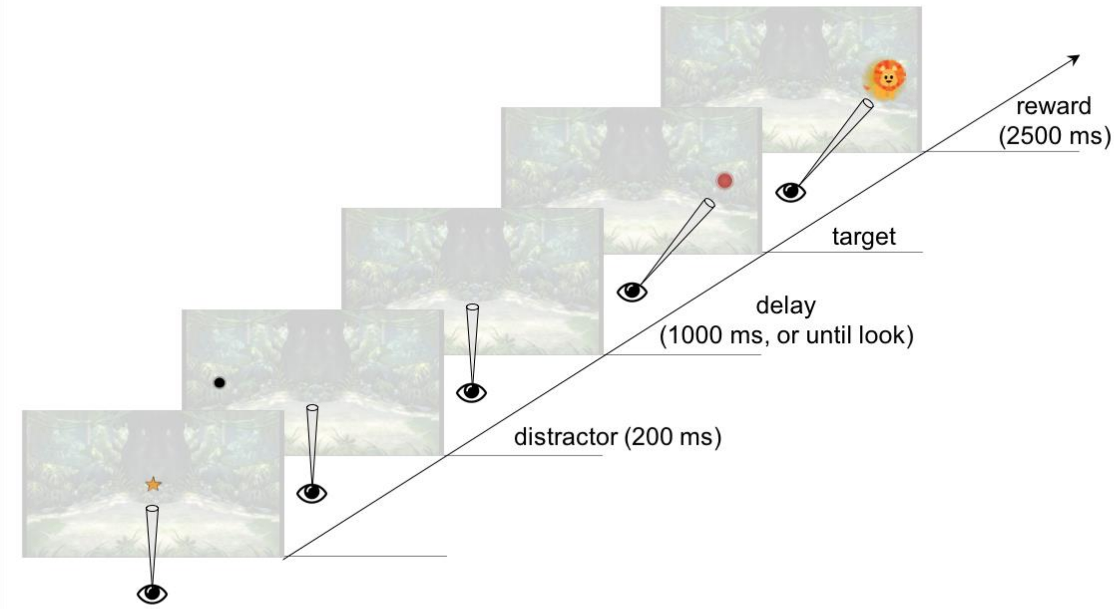

Figure 4. 2. Stimulus sequence for experimental trials in the Anti-Saccade Task. Stimuli drawn to scale. Every trial started with the central fixation stimulus onset.

The first 15 trials were segmented in two, first half ‘first 7 trials’ and second half ‘remaining 8 trials’. The proportion of looks towards the distractor not followed by an anticipatory look (= pro-saccades); of looks towards the distractor followed by an anticipatory look (= corrective saccades); and of anticipatory looks in the absence of a look to the distractor (= true anti-saccades, where inhibition of pro-saccades, as well as the production of contralateral saccades is needed) were calculated. These categories were mutually exclusive in a trial. Look proportion and latencies were averaged across each half trials to provide a more stable characterisation of individual differences.

Data from 5 children were not collected at the 12-month visit, 2 at the 18-month visit, and 2 at the 3.5-year visit due to technical problems or excessive fussiness or fatigue. Additionally, 5 children at the 12-month visit (2 HUs and 1 LU) and 4 at the 18-month visit (1 HU and 1 LU) were excluded because the number of valid trials on the task was less than 5.

Thirty-eight children (16 girls) who took part in the task were included in the main reported analysis – 24 HUs and 14 LUs based on longitudinal parent-report at all visits attended. Groups did not differ on the number of valid trials they yielded ($p > 0.3$). See Table 4. 2 for the number of valid trials and participants in each usage group.

Table 4. 2. Task related number of participants and number of valid trials, represented in terms of Mean (Standard Deviation), by age visit and longitudinal touchscreen media usage group. Difference between user groups (high and low users) was assessed on an independent samples t-test.

	Low users	**High users**	**Between-groups comparison**
Gap-overlap Task			
N, Mean number of trials (SD)			
At 12-months	14, 47 (15)	26, 44 (15)	n.s. (p = 0.5)
At 18-months	14, 50 (9)	23, 49 (14)	n.s. (p = 0.8)
At 3.5-years	14, 44 (9)	19, 50 (9)	n.s. (p = 0.09)
Antisaccade Task			
N, Mean number of trials (SD)			
At 12-months	13, 16 (5)	19, 16 (6)	n.s. (p = 0.9)
At 18-months	12, 12 (3)	22, 11 (3)	n.s. (p = 0.3)
At 3.5-years	13, 12 (2)	19, 11 (3)	n.s. (p = 0.3)

4.3.4. Analytic approach

As described in Chapter 2, the data analysis plan for the 3.5-year visit was pre-registered on the Open Science Framework (Open Science Collaboration, 2015) to facilitate replication and openness. In this pre-registration, effects in the outcome measures were planned to be tested with a repeated-measures ANOVA approach. However, in the current chapter, effects were tested using a Generalized Estimating Equation (GEE) model – this was because a GEE model allows inclusion of more data points than a repeated-measures ANOVA (which uses listwise deletion), thus allowing a longitudinal analysis which included more participants. Touchscreen media exposure differences in the described outcome measures of saccadic control were investigated separately for each task. Effects in the Gap-Overlap Task were tested using two separate GEE models to predict Disengagement and Facilitation using age and the longitudinal usage group (LUs and HUs) as predictor factors. Effects in the Anti-saccade Task were tested using separate GEE models to predict the proportion of anti-, corrective-, and pro-saccades, and the latencies to distractor (during pro-saccades) and to target (during anti-saccades), using half, age and the longitudinal usage group (LUs and HUs) as predictor factors. Main effects models were run first and then interaction effects were added in a second step. When age effects were found, they were followed up by Bonferroni corrected pairwise comparisons to assess differences between each age level.

See Appendix 4d for the pre-registered ANOVA analysis results at 3.5 years.

Results

4.3.1. The Gap-Overlap task – longitudinal touchscreen usage

A GEE model including usage group (HU, LU) and age (12, 18 and 3.5 years) as predictors of Disengagement showed a significant main effect of group: stable LUs showed a smaller disengagement effect (mean = 101 ms) compared to stable HUs (mean = 130 ms). There was no main effect of age and no interaction effect between user group and age. See results in Table 4. 3.

A similar GEE model including usage group and age as predictors of Facilitation showed a significant main effect of age. Bonferroni corrected pairwise comparisons showed significant shorter facilitation effects between 12 months (mean = -69 ms) and 3.5 years (mean = -22 ms, $p < 0.001$), but not with 18 months (mean = -52 ms, $p = 0.3$ and $p = 0.073$ respectively). There was no main effect of group, nor an interaction between group and age (see Table 4. 3).

To follow-up on the group effect on disengagement, separate GEEs models were conducted for saccadic latencies in the Baseline and Overlap condition.

A GEE model including group and age as predictors of saccadic reaction time in the Baseline condition showed a main effect of age. There were faster saccadic reaction times at 3.5 years (mean = 392 ms) compared with 12 months (mean = 425 ms, $p = 0.019$), but not 18 months (mean = 412 ms, $p = 0.12$ and $p = 0.6$ respectively). This model showed a significant main effect of group ($p = 0.026$; see Table 4. 3): HUs showed a faster baseline saccadic reaction time (mean = 396 ms) compared with LUs (mean = 425 ms) – see Figure 4. 3. There was no interaction effect between age and group.

For the Overlap condition, a GEE model including group and age as predictors of saccadic reaction time showed a main effect of age. Bonferroni corrected pairwise comparisons showed faster saccadic reaction times at 3.5 years (mean = 487 ms) compared with 12 months (mean = 548 ms, $p < 0.001$) and 18 months (mean = 537 ms, $p = 0.002$) measures, but no significant difference in SRT between 12 and 18 months ($p = 0.96$). There was no significant main effect of group, and no interaction between group and age (see Table 4. 3).

See descriptive statistics (mean and standard deviations) and figures of SRT across trial conditions and age visits for each longitudinal stable group in Appendix 4e.

There was no significant main effect of gender ($p > 0.2$) or of average Background TV ($p > 0.2$) on any of the outcome variables.

Table 4. 3. Summary of GEE Model Effects including longitudinal user group (high and low users) and age (12 months, 18 months, and 3.5 years) as predictors of the Gap-Overlap Task outcome measures. The analysis included 14 LUs and 26 HUs.

	Longitudinal usage group model Wald χ^2 (df), p value
Disengagement	
Age	4.505 (2), p = 0.105
Group	**3.949 (1), p = 0.047**
Age**Group*	0.329 (2), p = 0.848
Facilitation	
Age	**15.197 (2), p = 0.001**
Group	1.129 (1), p = 0.288
Age**Group*	0.404 (2), p = 0.817
Follow-up model on Baseline SRT	
Age	**7.62 (2), p = 0.022**
Group	**4.985 (1), p = 0.026**
Age**Group*	3.062 (2), p = 0.216
Follow-up model on Overlap SRT	
Age	**18.217 (2), p < 0.001**
Group	0.01 (1), p = 0.919
Age**Group*	2.894 (2), p = 0.235

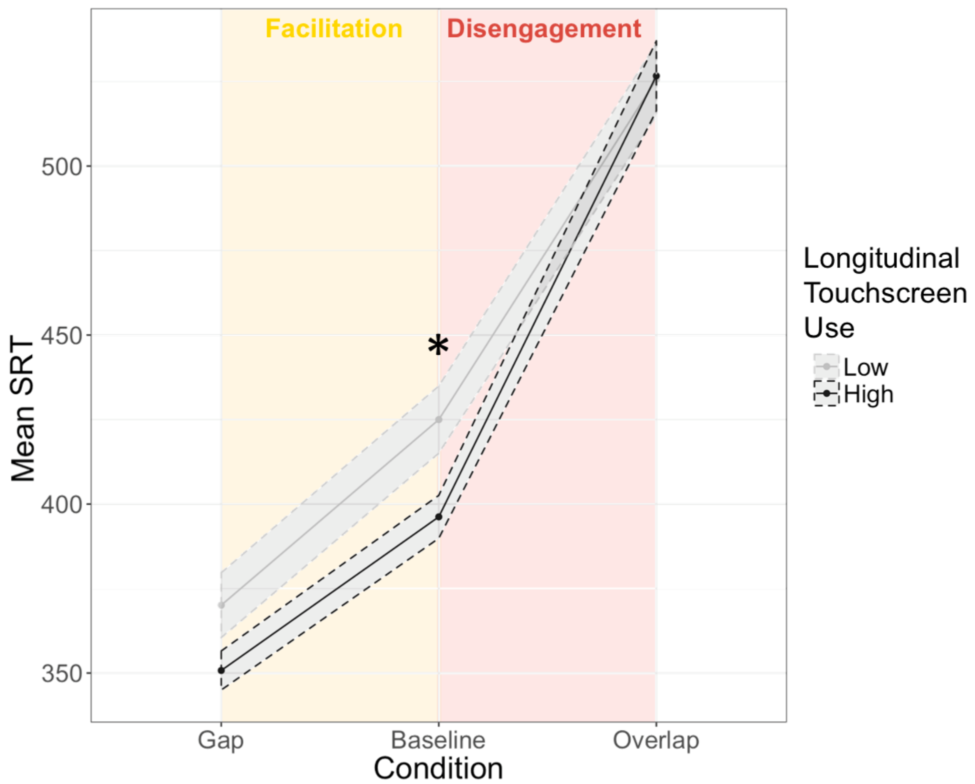

*Figure 4. 3. Mean Saccadic Reaction Time (ms) for each Longitudinal touchscreen use group (N = 40) as a function of trial condition in the Gap-Overlap Task. Shaded areas represent standard error of the mean. *p < 0.05.*

4.3.2. The Anti-saccade task– longitudinal touchscreen usage

Proportion of looking behaviour

A GEE model including usage group (HUs, LUs), age (12, 18 and 3.5 years), and task half (first, second) as predictors of proportion of anti-saccades showed a main effect of half (the proportion of anti-saccades in the second half of the task, mean = 0.46, was higher compared with the first half, mean = 0.12; see Table 4. 4) suggesting participants were learning the task. There was also a main effect of age. Bonferroni corrected pairwise comparisons showed that at 18 months (mean = 0.40) children were doing more anti-saccades than at 12 months (mean = 0.25, $p = 0.016$), but interestingly, at 3.5 years (mean = 0.22), they were doing significantly less anti-saccades than at 18 months ($p = 0.004$), with no significant difference between 3.5 years and 12 months ($p > 1$). There was no main effect of touchscreen usage group, but there was a significant interaction between half and group, with HUs doing less anti-saccades in the second half of the task compared with LUs across all ages (see Figure 4. 4), although a pairwise comparison for second half did not reach significance. There were no other significant interaction effects. See full results in Table 4. 4.

For proportion of pro-saccades (i.e. looks to the distractor not followed by an anticipatory look to the target location) there was a main effect of half (the proportion of pro-saccades decreased from the first half, mean = 0.71, to the second half, mean = 0.32), and a main effect of age, with Bonferroni corrected pairwise comparisons showing more pro-saccades as 12 months (mean = 0.61) than 18 months (mean = 0.44, $p = 0.007$) and 3.5 years (mean = 0.51, $p = 0.051$), while at 18 months and 3.5 years the proportion of these did not differ ($p > 1$). There was also an interaction effect between half and age, such that at 3.5 years the decrease in proportion of pro-saccades from the first half to the second half of the task was not as sharp as the decrease at 12 and 18 months (see Appendix 4f for the descriptive means for each half and visit). There was no main effect of usage group, nor any two-way interactions with group (see Table 4. 4).

For the proportion of corrective looks (looks to the distractor followed by an anticipatory look to the target location) there was a main effect of half (the proportion of corrective looks increased from the first half, mean = 0.16, to the second half, mean = 0.22), and a significant main age effect, with Bonferroni corrected pairwise comparisons showing that at 3.5 years (mean = 0.27) children were doing more corrective looks than at 12 (mean = 0.14, $p = 0.008$) and 18 months (mean = 0.16, $p = 0.001$), while at 12 and 18 months proportion of these did not differ ($p > 1$). There was also an interaction effect between half and age, such that the increase in proportion of corrective looks from the first half to the second half of the task was less steep with age, in a way that by 3.5 years there was no difference between each task half (see Appendix 4f for the descriptive means for each half and age point). There was no main effect of usage group, but there was a significant interaction effect of half and usage group, with Bonferroni corrected pairwise comparisons showing that HUs increased their corrective looks in the second half of the task (p = 0.011) while LUs proportion of corrective looks remained similar across halves (p > 1) – see Figure 4. 4. There were no other interaction effects (see Table 4. 4).

Table 4. 4. Summary of GEE Model Effects including group (high and low users) and age (12 months, 18 months, and 3.5 years), and task half (first, second) as predictors of the Anti-saccade Task outcome measures. The analysis included 14 LUs and 24 HUs.

	Longitudinal usage group model Wald χ^2 (df), p value
% Anti-saccades	
Half	**125.015 (1), p < 0.001**
Age	**10.803 (2), p = 0.005**
Group	0.142 (1), p = 0.706
Half**Group*	**4.755 (1), p = 0.029**
Age**Group*	1.46 (2), p = 0.482
Half*Age	3.297 (2), p = 0.192
Half*Age**Group*	0.828 (2), p = 0.661
% Pro-saccades	
Half	**230.336 (1), p < 0.001**
Age	**10.029 (2), p = 0.007**
Group	0.002 (1), p = 0.966
Half**Group*	0.048 (1), p = 0.827
Age**Group*	1.472 (2), p = 0.479
Half*Age	**11.001 (2), p = 0.004**
Half*Age**Group*	0.127 (2), p = 0.938
% Corrective looks	
Half	**5.007 (1), p = 0.025**
Age	**14.292 (2), p = 0.001**
Group	3.258 (1), p = 0.071
Half**Group*	**4.902 (1), p = 0.027**
Age**Group*	0.445 (2), p = 0.801
Half*Age	**6.577 (2), p = 0.037**
Half*Age**Group*	1.078 (2), p = 0.583
SRT to distractor (pro-saccade)	
Half	<0.001 (1), p = 0.993
Age	**17.695 (2), p < 0.001**
Group	**4.547 (1), p = 0.033**
Half**Group*	0.605 (1), p = 0.437
Age**Group*	1.725 (2), p = 0.422
Half*Age	5.937 (2), p = 0.051
Half*Age**Group*	1.689 (2), p = 0.43

	Longitudinal usage group model Wald χ^2 (df), p value
SRT to target location (anti-saccade)	
Half	**9.275 (1), p = 0.002**
Age	**33.689 (2), p < 0.001**
Group	0.935 (1), p = 0.334
Half**Group*	2.436 (1), p = 0.119
Age**Group*	0.382 (2), p = 0.826
Half*Age	3.437 (2), p = 0.179
Half*Age**Group*	0.793 (2), p = 0.673

See descriptive statistics (mean and standard deviations) and figures for the proportion of each look behaviour across age visits and longitudinal stable groups in Appendix 4f.

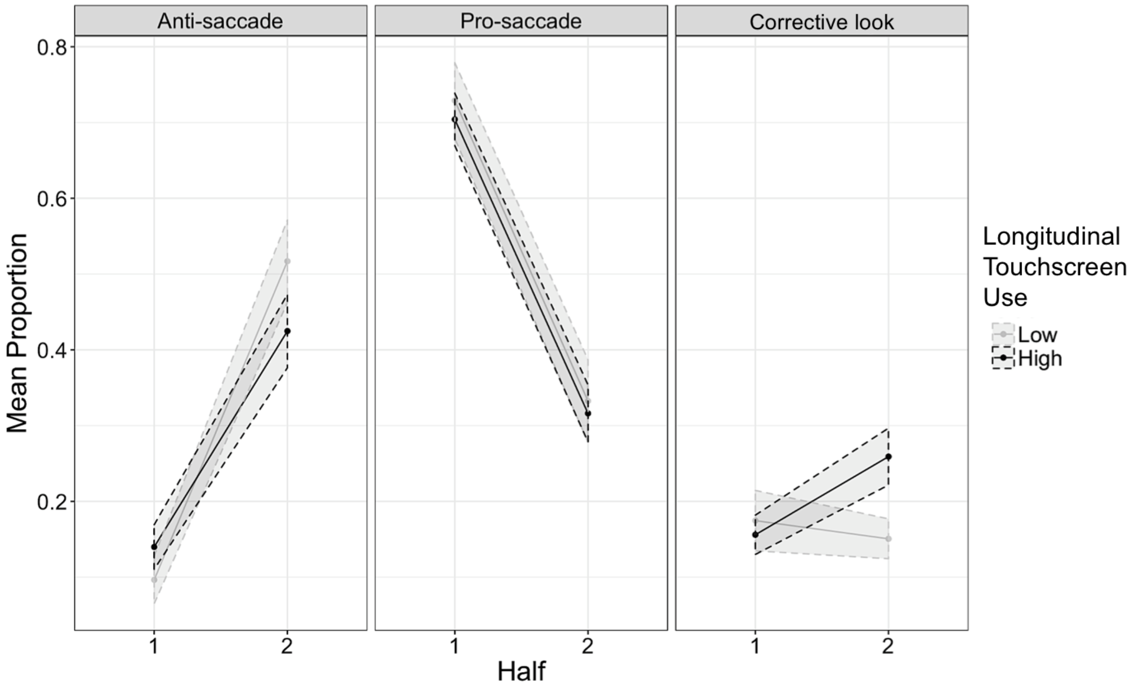

Figure 4. 4. Mean Proportion for each Longitudinal touchscreen use group (N=38) as a function of Task Half and look behaviour in the Anti-Saccade Task. Shaded areas represent standard error of the mean.

SRT to Distractor and Target

A GEE model including usage group (HUs, LUs), age (12, 18 and 3.5 years), and task half (first, second) as predictors of latency to saccade to the distractor (during a pro-saccade) showed a significant main effect of age. Bonferroni corrected pairwise comparisons showed that at 3.5 years (mean = 436 ms) children were significantly faster at looking to the distractor than at 12 (mean = 526 ms, p = 0.005) and 18 (mean = 548 ms, p = 0.017) months, while no differences between 12 and 18 months were found (p > 1). This model also showed a significant main effect of group; LUs were slower (mean =

535 ms) compared with HUs (mean = 480 ms). There was no main effect of half, nor any interaction effects – see full results in Table 4. 4 above.

A GEE model including usage group (HUs, LUs), age (12, 18 and 3.5 years), and task half (first, second) as predictors of latency to saccade to the target location in the absence of a prosaccade (i.e. during an anti-saccade) showed a significant main effect of half; the latency to saccade to the target side decreased from the first half, mean = 702 ms, to the second half, mean = 665 ms. The model also showed a main effect of age. Bonferroni corrected pairwise comparisons showed that at 18 months (mean = 619 ms) children were faster doing an anti-saccade than at 12 months (mean = 719 ms, $p < 0.001$), but interestingly, at 3.5 years (mean = 716) they were slower than at 18 months ($p = 0.010$), and in the same level of performance compared with 12 months ($p > 1$). This model showed no main effect of usage group, and no interaction effects between the predictors (see Table 4. 4 above).

See descriptive statistics (mean and standard deviations) for latency measures across age visits for each longitudinal stable group in Appendix 4g.

Background covariates

There was a main effect of gender only for the latency to saccade to the target location during an anti-saccade ($p = 0.023$), with girls being faster to anti-saccade than boys; results remained similar when controlling for it (see results in Appendix 4h).

There was a significant main effect of Background TV on the proportion of anti-saccades ($p = 0.002$), with higher average Background TV associated with fewer anti-saccades; on the proportion of pro-saccades ($p = 0.018$) and of corrective looks ($p = 0.001$), with higher average Background TV associated with more pro-saccades and more corrective looks; and on the latency to saccade to the target location during an anti-saccade ($p = 0.002$), with higher average Background TV associated with shorter latencies. When running the analysis with Background TV as a covariate all main and interaction effects reported above remained significant, apart from the main effect of half on the proportion of corrective looks, which became marginally significant ($p = 0.076$). See all GEE results where Background TV as a covariate in Appendix 4h.

4.3. Discussion

The current study confirms the link seen in Chapter 3 between infant and toddlers who have above-average use of touchscreen devices (high users average 54 minutes/day) and exogenous selective attention, with faster attention shifting to salient stimuli cues compared to low users (average 3 minutes/day). Evidence for a detriment in endogenous, goal-driven shifting of attention was less clear. The classic measures of endogenous attention – disengagement effect and anti-saccades made – showed poorer performance levels in high users. However, slow disengagement latencies were driven by faster baseline reaction times, rather than slower RTs in the overlap condition; and a lower proportion of anti-saccades went alongside a higher number of corrective looks (where children fixated both the distractor and anticipated the target). This may suggest that touchscreen use induces changes in the speed and selection of attention allocation over the visual scene. The reaction time advantage of orienting to pop-out items is not benefiting high users on demanding situations, i.e. when they have to release attention to a stimuli first, and when they have to inhibit a reflexive saccade to select a location on the opposite location instead.

On the **Gap-overlap Task,** high users of touchscreens were slower to disengage attention but this was due to them being faster when shifting attention on a no-competition condition, rather than being slow on an overlap-competition condition. This gives support to the idea that touchscreen media users are faster at shifting attention to exogenous cues which is in line with the study described on the previous chapter on the associations of touchscreen use and visual search performance (see Chapter 3) and supports the idea that exposure to touchscreen devices (which provide users with experience with highly salient and contingent content) leads to a greater attentional bias to salient stimuli. An effect on Facilitation was not found. Although an effect on the gap condition (which also indexes a shift to a peripheral salient stimuli) was not significant (p = 0.158, see Appendix 4i), given that the facilitation effect is a subtraction of gap and baseline latencies and baseline latencies differed between groups, it is reasonable to say that high users also had a tendency to be faster in this condition.

One of the most well-documented changes in playing video games is that it induces faster RTs (Castel et al., 2005; Dye, Green, & Bavelier, 2009a; 2009b; P. M. Greenfield et al., 1994). This literature also showed that action video game players (both adults and children) experience a high interference effect (a higher relative difference between congruent and incongruent conditions in certain attention tasks; Dye, Green, & Bavelier, 2009b; Green & Bavelier, 2003). Rather than interpreting these effects as a poorer control of attention, the authors have argued that this is indicative of greater available attentional resources, leading to over-selectivity of both congruent and incongruent items. However, it is important to highlight that in the aforementioned cases, greater interference effects were accompanied by much faster reaction times in **all** conditions. This highlights also that it is important to study within-subjects measures (such as the disengagement effect) in light of the between-groups baselines. In this study, although a generalised speed of processing increase was not found, the between-subjects effect on disengagement is reflecting the magnitude of the baseline RTs rather than a difference in the disengagement processing in the overlap *per se*. So the results presented suggest that HUs took more time than expected considering the RT advantages they present in the baseline; or that they responded comparatively slower in the overlap compared to their baseline. It is essential to examine the RTs by condition in the gap-overlap task, and not simply rely upon difference scores, and it suggests caution when interpreting disengagement and facilitation effects in other studies that do not report condition scores, to correctly interpret effects.

On the infant **Anti-saccade Task**, high users of touchscreens performed fewer anti-saccades, with a strategy for corrective behaviour that still showed efficient anticipation of the target. High users were also faster to perform a pro-saccade (look to the salient distractor), and this speed advantage might function as a trigger for the corrective behaviour (see below). Interestingly, high users performance on this task was remarkably similar to the performance acquired with age. While at 12 and 18 months, children were able to inhibit looking at a distractor to look to an anticipated, more rewarding, opposite stimuli, older children got quicker to shift to the distractor and consequently produced fewer anti-saccades and more corrective looks. This suggests that by this age, all children were quick enough to get to the target side on time for the target to be anticipated, and the reward to be given quicker, while still looking to the salient distractor. The similar direction of effects between age and touchscreen usage suggests that high users quickening of exogenous attention early in life already enables them to opt for the second strategy (corrective look) at 12 and 18 months.

However, it is important to discuss the appropriateness of the infant Anti-saccade task at 3.5 years. It is possible that the design specifications (target onset timing, = 1000 ms after distractor offset) of the task were not sensitive enough to elicit or reveal strong inhibition detriments in HUs, and that it allowed children with faster orienting latencies to opt for an over-selective behaviour (look to distractor and target location) without punishment to performance (they still anticipated the target). In this study, this was a necessary decision to ensure RTs and probabilities could be compared across visits. Furthermore, the corrective saccades behaviour is interesting in itself, and suggests that participants learnt what they should be doing in the task. Corrective behaviour on the anti-saccade task was also found in other studies with young children (Scerif et al., 2006).

Given the lack of interaction effects between group and age, the results from this study might also suggest that a pattern of use over time (reflecting high levels of prolonged exposure) is specifically associated with the top-down difficulties, as it was shown before in the context of television viewing patterns and externalizing problems (including hyperactivity, which might index endogenous control problems) across 18, 24 and 30 months of age (Verlinden et al., 2012).

In sum, these findings indicate that the visual attention system of toddlers with high touchscreen use may be more exogenously driven than the one of no/low use toddlers as evidenced by faster saccadic reaction times in baseline gap-overlap trials and pro-saccades. Endogenous control, at least in regards to the way that the tasks were traditionally implemented, appears, at first sight, impaired in the high users, with slower disengagement of attention (relative to their baseline) and difficulty to inhibit an automatic response (although still achieving the task goal).

There are at least two possible explanations for these findings. One is that the endogenous differences observed on disengagement and inhibition are solely driven by high users' exogenous speed difference which allows them to use a different attentional strategy while not having detriments to overall performance. However, while high users are faster in the exogenous conditions of these tasks, it is intriguing that they do not benefit from this faster process on more demanding conditions. In this sense, it can be that high users are using their faster shifting speeds to compensate for endogenous differences, or that their strategy to give priority to automatic bottom-up processing is displacing increasing competency of top-down processes. Whether this would lead to poorer performance in real-world tasks of goal-directed attention control behaviour and executive functioning remains to be tested.

Altogether the results presented seem to suggest that touchscreen use was associated with faster attention shifting to saliency, independent of the type of use. The use of a longitudinal lab-based design provided a detailed profile of attention performance possibly acquired by using a touchscreen early in life. However, this approach has clear limitations. First, this study was observational in nature and not interventional, so the hypothesis that children who have an increased sensitivity to salient stimuli (and a relatively reduced top-down attention control) are more drawn to touchscreen media technologies is as likely as the hypothesis that a sensitivity to saliency (and relative top-down difficulties) is acquired by using a touchscreen. An investigation of the direction of the association and its causality remains to be conducted. Another limitation is that the assessment of touchscreen use was taken from a single parent-report question; however, it was strongly correlated with media diaries obtained from parents prior to the visits (see Chapter 2).

A further important limitation of this study concerns the screen-based context where the outcome measures of attention control were obtained. High users of touchscreens made faster reflexive saccades to perceptually salient formal features with concomitant differences in the use of top-down and goal-driven attention, and the longitudinal nature of the study suggests that this attentional "strategy" was acquired through the experience with the touchscreen devices. Given that the outcome measures were obtained while children were watching stimuli on a screen, it is not known if this acquired "strategy" is context-specific (i.e. only applied when watching a screen), or if it translates to "real-world" settings where saliency might appear in a form of distraction and top-down executive processes are required more actively to control behaviour in a goal-driven way (Choudhury & Gorman, 2000; Wass, 2014b). Future work should thus investigate the associations of touchscreen use and top-down control of behaviour (i.e. executive functioning) in the "real-world".

In conclusion, high users of touchscreens showed poorer performance on measures of endogenous attention but this seemed to be driven by their faster shifting to peripheral salient cues. The results of this study suggest that exposure to touchscreen devices may be associated with a specific attentional strategy which is characterised by a quickening of attention to peripheral salient onsets, with concomitant detriments to measures of endogenous attention control. Future work is needed to demonstrate causality and to test whether an attentional profile that benefits saliency-driven attention and displces endogenously-driven attention, seen in screen-based contexts, translates to "real-world" settings. If supported by future studies this finding might have important implications for the development of digital media content and for child health agency bodies wanting to promote evidence-based policies.

4.4. Summary of Chapter 4

- This chapter tested the association between longitudinal stable touchscreen media use (based on usage across infancy and pre-school visits) and attention control.
- Attention control was measured in two infant saccadic control tasks and dissociated in terms of exogenous (saccadic latencies in the baseline condition of the Gap-Overlap Task, and to a salient distractor in the Anti-saccade task) and endogenous (disengagement of attention on the Gap-Overlap Task, and anti-saccade behaviour) measures.
- Toddlers with a high use of touchscreens across visits showed showed poorer performance in associated measures of endogenous saccadic control: higher disengagement effect in the Gap-Overlap Task and reduced anti-saccade behaviour in the Anti-saccade Task.
- The same toddlers showed faster performance on measures of exogenous attention: faster saccadic latencies in the baseline of the Gap-Overlap Task and faster saccadic latencies to the distractor in the Anti-saccade Task.
- The reduced endogenous attention seems to be driven by the increased exogenous attention.
- The speeded bottom-up response did not benefit high users in competition situations in the Gap-Overlap task (i.e. the overlap condition).
- Increased experience with touchscreen media is associated with a specific attentional behaviour: high users of touchscreens opt for a corrective behaviour of looking to the distractor and looking to the target location before its appearance.
- The “real-world” consequences of these differences should be addressed by studying performance in executive function tasks that require top-down/ internally-driven behaviour.

Chapter 5:
At 3.5 years, high users of touchscreen devices have reduced cognitive flexibility

5.

5.1. Introduction

At age 3 years, children start to show an increased ability to self-control attention and behaviour in order to meet a goal (i.e. executive functioning, EF; Carlson, Zelazo, & Faja, 2013). EF is a set of important abilities in school and life and is strongly associated with social and cognitive outcomes (Blair & Razza, 2007; Bull, Espy, & Wiebe, 2008; Eigsti et al., 2006; Diamond & Lee, 2011; Mischel, Shoda, & Rodriguez, 1989; Moffitt et al., 2011; Ponitz, McClelland, M M, & Morrison, 2009). It includes distinct but inter-related processes such as working memory (WM, the ability to keep and *update* information in mind), inhibitory control (IC, the ability to *inhibit* an action or thought), and cognitive flexibility (CF, the ability to *shift* mind sets or rules of behaviour; Miyake et al., 2000; Miyake & Friedman, 2012). A lot of research has provided evidence of early emergent abilities of executive functioning in the first years of life, with a great amount of development occurring during the pre-school years (Best & Miller, 2010; Diamond, 2013; Garon et al., 2008) where observable competencies are gained in all distinct EF processes. Throughout childhood and adolescence, it is believed that there is continued maturation of these skills (Luna, Garver, Urban, Lazar, & Sweeney, 2004).

There is some indication that modern media, including television and interactive play, might influence the development of executive functions. This chapter starts by reviewing the concept of executive function and its components, and then discusses studies of both the long-term and short-term influences of media use on child's EF. It then presents a study investigating whether concurrent group-level differences in executive function (dissociating WM, IC, and CF processes) occur between young children who have different habitual levels of touchscreen use, irrespective of the mode of use on the devices. It ends by discussing how experience with touchscreen media might exert effects on this set of mental processes.

Both the brief introductory review on EF, the hypothesis proposed, and the protocol design in this chapter, were structured according to a fractioned model of EF and focused on the three putative EF components: i.e. working memory (WM), cognitive flexibility (CF), and inhibitory control (IC). Given that there is variation in the developmental timing and trajectories of these EF abilities (Carlson, 2005; Diamond & Ling, 2016; Garon et al., 2008; Klenberg, Korkman, & Lahti-Nuuttila, 2001; Murray & Kochanska, 2002; Rosso, Young, Femia, & Yurgelun-Todd, 2004), it seemed of value to study whether they were differently-associated with touchscreen media use, as this may inform about the underlying developmental mechanisms. However, these components are not always dissociated in prior studies researching other media platforms (i.e. television and video-games), which often made use of composite measures on EF tasks. For that reason, I first summarize the literature in regards to each EF construct, the methodologies used to measure them in toddlers and pre-school children, and the developmental overlap between these latent constructs, which gives rise to an integrative EF model that accounts for a unitary view (Miyake et al., 2000). I then proceed to present the relevant literature concerning EF and children's media environment that shaped the hypotheses.

Working memory

Working memory has been defined as the ability to update or manipulate information in mind so as to use it to complete a task (Baddeley, 1992). In early development, before infants can actively update information in mind, they need to be able to hold that information there over a delay. This limits WM to task *maintenance* abilities in the infancy literature, measured by tasks, such as delayed response tasks, where an interesting object is hidden and the infant is allowed to search for it after a brief delay. Based on this task, WM abilities have been shown as early as 6 months of life (when an object is hidden in view of the infant in one of two possible locations and using a short delay; O'Gilmore & Johnson, 1995; Pelphrey & Reznick, 2003; Pelphrey et al., 2004); and increasing improvements in memory capacity observable for example, in the longer delays infants and toddlers can handle the encoded information in mind (Diamond & Doar, 1989), or the number of possible locations they can handle (Pelphrey et al., 2004). *Updating* information in mind, a crucial aspect of WM, develops later than simple maintenance, around the second year of life. In a more demanding version of the delayed response task, one that taxes *maintenance* and *updating* of task set, the reward is hidden out of sight of the child in one of two locations and then alternated after every successful retrieval (delayed alternation). Children struggle with this task even after their third birthday (Espy, Kaufmann, McDiarmid, & Glisky, 1999; Stahl & Pry, 2005). Another example of *updating* tasks used with pre-schoolers are self-ordered searching tasks (P. J. Anderson & Reidy, 2012; Hughes, 1998; Hughes & Dunn, 1998) where the child has to generate and monitor a sequence of choices to search efficiently for multiple rewards hidden in multiple locations (e.g. find 6 rewards in 8 visually distinct pots that are scrambled every trial). Developmental improvements have been reported for these tasks, as children get increasingly accurate and more competent in keeping track of a larger number of locations (Diamond, Prevor, Callender, & Druin, 1997; Ewing-Cobbs, Prasad, Landry, Kramer, & DeLeon, 2004; Hongwanishkul, Happaney, Lee, & Zelazo, 2005). WM capacity continues to increase beyond the pre-school years (Hughes, 2013).

Inhibitory control

Inhibitory control is a multi-faceted construct involving withholding or delaying a response. This ability ranges from suppressing a simple dominant response for a prolonged time (like touching an attractive toy), which can be observable in the first year of life; to quickly coordinating inhibition-and-activation of a response (e.g. when children have to suppress an action that they are doing repeatedly), which develops quickly around 3 years of age.

Kochanska and colleagues have extensively researched IC in early childhood, from 8 months to school entry (Kochanska et al., 1996; 2000; Kochanska, Tjebkes, & Fortnan, 1998). They found that individual differences in IC are consistent across different contexts (Kochanska:1996va) and relatively stable over time (Aksan & Kochanska, 2004; Joyce et al., 2016; Murray & Kochanska, 2002).

IC is often measured in infants and toddlers with delay-type control (waiting) tasks, e.g. prohibition tasks (Friedman et al., 2011), which usually calls for suppression of an emotionally-charged response (e.g. to NOT touch an attractive toy) and are usually "hot EF" tasks (Mulder et al., 2014). The ability to not touch an attractive toy upon an instruction is observable with short delays already in a small proportion of 8-months-olds, but during the third year of life children can inhibit themselves the majority of the time (Kochanska, 2002; Kochanska et al., 1998). A more appropriate version of this task for pre-school children are delay of gratification tasks – in these tasks children are asked to suppress the action of eating a treat, or opening a present, for varying durations and task manipulations (variations include a choice of when to break the rule or the number of rewards received). The length of time children can delay their response has been shown to improve throughout the pre-school period (Carlson, 2005; Kochanska et al., 2000 Kochanska et al., 1996).

Another type of, quite different, IC involves dynamically coordinating inhibition and activation of a response. This is the case for initiating-suppressing tasks (e.g. Go/No-Go) which involve infrequently inhibiting an action, like tapping a character on a screen, while frequently needing to activate that response; or for tasks which involve inhibiting a prepotent (dominant) response to respond according to an arbitrary rule (e.g. sorting large spoons within small bowls and small spoons within large bowls).

Evidence on this ability shows a jump in performance during the fourth and fifth year of life (Carlson, 2005; Carlson & Moses, 2001; Carlson, Moses, & Claxton, 2004b; Dowsett & Livesey, 2000). Earliest but more simple forms of resolution of conflict between dominant and subdominant abilities have been demonstrated during the first year of life, in studies that showed that infants below 12 months demonstrated some conflict resolution by retrieving an object from a transparent container through an opening on the side (first needing to inhibit the tendency to reach directly in a straight line for the object = dominant response); and by evidence of inhibition of automatic saccades and production of anti-saccades in the infant Anti-saccade Task (Johnson, 1995), as was seen in the previous chapter (the participant has to inhibit a pro-saccade (a dominant response) while activating an incompatible one, an anti-saccade). Because these tasks are emotionally neutral and involve more abstract goal representations, they are considered "cool-EF". More complex response inhibition, which makes use of mental representation to regulate response, continue to develop and improve after the pre-school period (Luna et al., 2004).

It is important to note that the literature has been challenging the unifying nature of this construct. For example, Delay of Gratification tasks often do not correspond to performance on other EF tests, even response inhibition ones (Carlson & Moses, 2001; Diamond & Lee, 2011; Huizinga, Dolan, & van der Molen, 2006; Mulder et al., 2014; Murray & Kochanska, 2002); and even inter-correlations among cool-IC task in adults are very difficult to find (Gärtner & Strobel, 2019).

Cognitive flexibility

Children show striking limitations in their ability to break out of habitual ways of thinking and behaving and overcome perseveration, but this is considered a crucial aspect of development and is predictive of success in life (Blair & Razza, 2007; Moffitt et al., 2011). Within the pre-school literature, cognitive flexibility is usually operationalized as the capacity to respond based on one rule, and then switch to another (almost always the shift is imposed by an external source). Thus, CF tasks most often involve two phases of the task, a pre- and a post-switch phase, with the first one requiring participants to learn an arbitrary stimulus-response association (mental set or rule) and hold it in mind (= maintaining in WM). The second phase involves shifting to a new, related but conflicting, mental set, which require disengagement from the previous set (= inhibiting previous rule).

Some shifting abilities emerge during infancy. Successful performance on the A-not-B task (Piaget, 1954) is one of the earliest forms of response shifting. In this delayed response reversal task, infants have to form a simple response set (search for a toy in location A) and then shift response to a new set (search in location B). Infants as young as 7 months can succeed in the task over a brief delay, and there is a linear increase in the delay they can tolerate before persevering in the first response set over the first year of life and the pre-school years (Diamond, 1985; Thelen et al., 2001).

However, an important aspect of CF, conflict resolution between mental sets, only seem to emerge between 2-3 years of age, and gradually increases to allow resolving conflict while shifting, around the age of 3 to 4 (Blakey, Visser, & Carroll, 2016; Garon et al., 2008; Johansson, Marciszko, Brocki, & Bohlin, 2016; Zelazo, 2006). As children approach school entry, they become increasingly competent in shifting between strongly conflicting response sets. This is particularly evidenced by the literature of the DCCS task, a task where children have to sort test cards that vary on two dimensions (e.g. colour and shape) into target cards that conflict on the same dimensions. Findings from the DCCS and similar dimension shift tasks (Doebel & Zelazo, 2015; Zelazo et al., 2003) show that between 3 and 4 years of age children acquire the ability to shift from the pre-shift rule (e.g. sort according to colour) to the post-shift rule (sort by shape).

During the pre-school years, CF seems to build upon the other two EF components. For children to perseverate they need to maintain a response set in mind, so the construct of CF is closely linked to that of WM (Blakey et al., 2016), with additional demands relating to shifting. Failures on the DCCS have also been appointed to WM deficits, in a way that the post-shift representation is not strong enough in WM to overcome perseveration (Munakata, 2001). At the same time, the emergence of CF has also been explained by increases in IC, because successful shifting requires the inhibition of attention to the pre-shift set or response (attentional inertia account; Diamond & Kirkham, 2005; Kirkham et al., 2003). However, other experimental studies have failed to show that IC (Jacques, Zelazo, Kirkham, & Semcesen, 1999; Perner & Lang, 2002) or WM (Perner & Lang, 2002; Zelazo et al., 2003) underlined alone performance on these tasks. Although WM and IC share some common variance with cognitive flexibility, it seems that the three can yet be discriminated and may have different antecedents (Garon et al., 2008; Hendry et al., 2016; Joyce et al., 2016; Kochanska et al., 2000).

How EF is organised and deconstructed is a matter of much debate within the literature. As it was described, the three aforementioned components overlap quite substantially and built upon one another. A very influential model by Miyake and colleagues in 2000, the *unity-yet-diversity* model, provided a framework for the organization of EF around the three aforementioned components sharing common and unique variances across the lifespan, and a good amount of research supported this model in adults and older children. More recently, however, there was a shift towards a view that includes IC in the "common EF" factor (Miyake & Friedman, 2012). In infancy through pre-school, the structure of EF is yet less stable and coherent (Hughes, 1998; 2002), possibly because EF processes are not yet fully functional and integrated. An additional problem, often described as the task impurity problem (a task used to measure a construct often puts some demands over another construct), confounds results. Also, the three constructs seem to be strongly bound to the construct of attention control or executive attention system (once thought to be the common-EF process). This leads to much debate around the best model that describes EF development: if a single EF construct (as found as the best fit in many studies with EF tasks batteries; Hughes et al., 2009; Shing et al., 2010; Wiebe et al., 2008; 2011); or one that includes foundational abilities and emerging constructs (Hendry et al., 2016) for a complete review and Figure 1. 2 in Chapter 1 for their conceptual model).

In media use studies, most likely because of the overlap of constructs and the task impurity problem, a unitary view of EF (and one that sees attention has a central component), is often used to study the immediate and the long-term impact of media devices. I will briefly present these studies and their methodological approaches for the remainder of this chapter introduction.

Television is still one of the most popular media activities for young children. As discussed in the previous chapters, most of the evidence about television viewing shows that more exposure is associated with concurrent and/or long-term attention problems (see Chapter 1 section 1.3.1) using measures that overlap quite considerably between executive attention and the construct of EF – e.g. parent-report measures of attention difficulties (Zimmerman & Christakis, 2007), and sustained attention during free-play (Geist & Gibson, 2000; Kostyrka-Allchorne, Cooper, Gossmann, Barber, & Simpson, 2017c). But a few studies have further supported a specific negative association between television exposure and lab-based measures of EF, both for child-directed amount of televsion viewing and a composite measure of EF (including cool-IC and WM; Nathanson et al., 2014) and overall household and adult-directed television viewing and a measure of IC and CF (Barr et al., 2010). In addition, some evidence from experimental studies manipulating programming pace (in terms of screen changes and novelty rate) have generally shown a short-term negative impact on composite measures of EF (including measures tapping IC, both delay of gratification and response inhibition, WM, and CF; Kostyrka-Allchorne, Cooper, Kennett, Nestler, & Simpson, 2019b; Lillard & Peterson, 2011; Lillard, Drell, Richey, Boguszewski, & Smith, 2015a; Lillard, Li, & Boguszewski, 2015b), although one study failed to show an impact on IC measured by the Day/Night task (Kostyrka-Allchorne, Cooper, & Simpson, 2019a).

These negative associations have been explained by both the passivity of television and the time-displacement of better opportunities to actively explore the environment, and by the inappropriateness of the content watched, which poses that rapid scene changes, salient stimuli, and surprising events favour bottom-up orienting of attention, thus activating this type of processing, and at the same time overloading resources for executive processes.

In a different line of research, some studies, through cross-sectional and experimental designs, have found a positive impact of action video-gaming on a range of cognitive outcomes, particularly in terms of processing speed and accuracy of visual information (Castel et al., 2005; Dye, Green, & Bavelier, 2009a), and attentional capacity and allocation, including better attention shifting, which is related to CF (Green & Bavelier, 2003). This led to some theories around the idea that contingent and demanding media, could resemble cognitive training environments, and directly train executive attention abilities. Although computer training games have shown some promise in terms of executive functioning (Nouchi et al., 2013; Rueda et al., 2005), only a few studies have investigated habitual playing of action or first-person video games and EF, showing better abilities on WM and CF (Colzato et al., 2010; 2013). However, it is unclear whether the patterns of associations with EF seen in relation to television or video-games are seen with touchscreen devices use given that the platforms differ in a varied of aspects.

In terms of touchscreen use in young children, one study has tried to investigate the short-term influences of interacting with a touchscreen on EF, with their results showing better performance on delay of gratification and WM after playing an educational app, compared with watching an education or entertainment televsion program on an iPad, but with no effects on CF (Huber, Yeates, Meyer, Fleckhammer, & Kaufman, 2018b). Because this study did not apply an appropriate control condition (e.g. reading) neither a pre/post-test design, it is unclear whether the findings are explained by an attenuation of the EF media impact after touchscreen compared with television viewing, or because the interactive activity boosted EF. Another very recent study investigated whether the naturalistic experience of passive (i.e. program viewing on any platform, TV set or a touchscreen device) or active (playing with *apps* on touchscreen-like platforms) media was associated with reduced EF (WM, IC, and CF measured in the lab) one year later in pre-schoolers. In contrast to the television literature presented before, results did not show a longitudinal association between passive use and EF; however, high active users (> 30 min/day of app playing) showed poorer cool-IC (indexed by performance on a Go/no-go task) one year later, relative to low users and non-users (McNeill et al., 2019). Quite surprisingly, the study did not present results concerning concurrent associations between habitual touchscreen media exposure and EF, neither dissociated viewing conventional programming on a screen (television) and on touchscreen media; this is the pressing aim of this chapter.

The current study

In the previous chapters, I have shown repeatedly a bias to bottom-up attention orienting (Chapter 3 and 4), which led to the displacement of opportunities for top-down attention control seen in Chapter 4. Given that these results were based on screen-based measures of attention allocation, the question emerging from it, and answered in this chapter, was to what extent these biases and associated top-down difficulties were observed in "real-world" situations that demanded executive functioning. If touchscreen use disrupts EF performance in pre-school, as it has been shown before with other media devices such as television (Barr et al., 2010; Kostyrka-Allchorne, Cooper, Kennett, Nestler, & Simpson, 2019b; Lillard, Drell, Richey, Boguszewski, & Smith, 2015a; Nathanson et al., 2014) and active playing with touchscreen media platforms (McNeill et al., 2019), then I predict differences in all components of EF in children who have high daily touchscreen use (HU) compared to matched children with low daily touchscreen use (HU), in a way that children with high daily touchscreen use will demonstrate worse EF performance compared with children with low daily touchscreen use.

5.2. Method

This study is part of the longitudinal project described in Chapter 2 and uses data collected at the 3.5-year visit. The focus of this study is on the associations between touchscreen media use and Executive Function in pre-school children, therefore only the behavioural data from the visit at 3.5 years will be included. However, for the exploratory analysis of longitudinal touchscreen use associations, touchscreen media use groupings across visits (described in Chapter 4) will be included when appropriate.

5.2.1. Participants

Participants in this study were part of the TABLET Sample (see Chapter 2) and had come to the Birkbeck *Babylab* at least for the 12 months visit. They were informed of the recruitment for this follow-up study four months before testing started, via a newsletter email. They were later personally invited to come to the lab via e-mail and phone calls. The 3.5 year visit testing period took place from March to September 2018. From the initial study cohort (N = 56), forty-nine children were available to schedule a lab-visit. However, one child was excluded from the study due to a developmental diagnosis (Mild Cerebral Palsy) identified at the time of testing; the other two were unavailable to attend the lab visit on the day, but one contributed with questionnaire data prior to the visit. These three children were not included in further analysis. The forty-six (who contributed with data for the current study) sample characteristics for age and background measures are presented in Chapter 2 Table 2. 3.

5.2.2. Touchscreen media use assessment and usage groups

As presented in Chapter 2, parents reported on their infants' media use via an online questionnaire before coming to the Babylab, at 12, 18, and 3.5 years.

In this questionnaire, parents were asked about the duration of their child's use in hours and minutes: 'On a typical day, how long does your child spend using a touchscreen device (tablet, smartphone or touchscreen laptop)?' (Bedford et al., 2016). At 3.5 years, the parent-report measure of touchscreen use duration was significantly and moderately associated with the amount reported on the 24-hour media diaries (also filled online, see Chapter 2 Table 2. 5), $r_s(44) = 0.62$, $p < 0.001$; which supports the parent-reported measure of touchscreen use.

The sample was divided into two groups based on a cut-off system using the median of the parent-report daily touchscreen time at 3.5 years. Children who were in the top cut of exposure (greater than or equal to 15 min/day) were coded as "high users" (HUs) whereas the children in the low cut (less than 15 min/day) were coded as "low users" (LUs). This group variable was the main independent variable of interest.

The child media environment is dynamic, and likely to vary depending on age, level of development and family characteristics (e.g. change of routines such as starting attending nursery or parents going back to work; Valkenburg & Peter, 2013). To investigate whether the associations between touchscreen media use and EF were specific to recent naturalistic use, or associated with prolonged use, the longitudinal stable touchscreen use group, coded based on the three longitudinal TABLET visits and described in Chapter 4, was added as a predictor in follow-up models.

5.2.3. Background variables

The dichotomous groups for touchscreen use (HUs and LUs) at 3.5 years were matched on the following background demographic variables: mothers' education (0 = below degree; 1 = degree level or above), concurrent age (days), and gender (0 = boy, 1 = girl). General development level, assessed by the Mullen Scales of Early Learning (MSEL) at the 12 months, was not done at this visit, except for the Visual Reception (VR) scale. Both the 12-months MSEL Composite Score and the 3.5 years VR T-score were matched between groups.

Background TV viewing, in minutes per day, assessed through parent-report on the online media questionnaire by asking the question: 'On a typical day, how long is a TV switched on in your home?'), was not matched between groups, with parents of high users reporting higher total household television. In follow-up analyses, this variable is going to be included as a covariate in a follow-up model and reported if a significant main effect with the EF measures is found.

5.2.4. Stimuli and procedure: EF measures

The behavioural tasks used in this study were part of a 3-hour protocol described in Chapter 2. Children were given regular breaks throughout the session if needed (e.g. to snack, to go to the toilet). The EF tasks were completed in the middle of the session, ~30-45 minutes after arrival to the *Babylab*, to allow the child to already be familiar with the experimenter but not tired. The EF battery (~30 minutes) was completed in a fixed order (first the touchscreen-based tasks, i.e. Delayed Alternation, and Go/No-go; followed by the table-top tasks, i.e. Spin the pots, Snack Delay, DCCS, and Glitter Wand), except for three children who did the table-top tasks before the touchscreen-based ones, due to technical problems with the monitor. Two additional tasks were completed but not analysed in this study (the Switch task, which was completed at the end of the touchscreen-based protocol, and the Problem-solving box Task, which was completed at the end of the table-top EF tasks) – these tasks were designed to assess CF and problem-solving respectively, but because they have not been validated yet they were excluded from this study. In addition, the Anti-saccade task was completed before the EF tasks, during the first part of the session. All tasks were administered by the author. During administration of the tasks used in this study, children were wearing an unobtrusive sensor strap to collect heart rate data and a sensor watch to collect activity (not reported here).

All EF tasks (except for the Anti-saccade) were administered in a big testing room, free from distractions and were filmed with a three cameras system (in three corners of the room). The parent was present in the room for all tasks but was instructed to fill out standardized questionnaires (i.e. the Vineland Adaptive Behavior Scales, and the Strengths and Difficulties Questionnaire), to not prompt or encourage the child at any point, and to sit out of direct eye line from the child. The experimenter encouraged children to remain focused on each of the activities. During the task, the experimenter level of response was matched to the child's – for example, some children got very excited and wanted to laugh out loud with her, while others worked in quiet concentration.

Vivotek SD8161 cameras with integrated Olympus ME33 boundary microphones were positioned in three different locations around the room to record performance during the EF battery. During testing, a research assistant (blind to group status) recorded online observations of the child's performance on all tasks, on testing notes sheets appropriate for each task.

5.2.4.1. Measures of EF – touchscreen-based tasks

The touchscreen-based tasks were computerized games, administered on a desktop touchscreen monitor (15-inch LCD Elo Entuitive, 1024 x 768 Hz, 304.1 x 228.1 mm useful screen area) connected to a Acer Aspire VN7-592G PC (Intel Core i5-6300HQ CPU @ 2.30GHz, with 16GB RAM and 64-bit operating system) running Windows 10 Home with a VGA cable. Audio was presented through two speakers hidden behind the monitor on each side. The tasks were coded by a project collaborator (Dr. Alexandra Hendry) in EPrime vn 2.0 (Professional, 2.0.10.353), and presented using E-Prime 2.0 Professional (Psychology Software Tools, Sharpsburg, PA).

The touchscreen tasks were introduced to the child as computer games by saying "We're going to play some games on my special computer. First, I'll show you how to play the games, then you can have a go". The session started with a short warm-up task to familiarise the child with the touchscreen, and screen for difficulties in tapping. The experimenter said, "First we're going to practise using our tapping finger. Do you have your tapping finger ready? Let's tap some bubbles!". Once the child had successfully tapped 5 bubbles the first task (Delayed Alternation, see below) launched.

The child was seated at a child-appropriate chair in front of the monitor, which was mounted on a low table (see Figure 5. 1) with the experimenter sat next to them. After instructing and demonstrating each task the experimenter sat back away from the computer (but so that the child could still see her) so that the child was not biased to/away from the side that she was sitting on. For all children, the experimenter always sat on the same side of the computer.

Figure 5. 1. Illustration of a child doing the screen-based tasks.

If at any point the touchscreen did not detect a response the child was prompted to try again. If they tapped too gently the experimenter said "Try again with a big push"; or if they used their fingernail or multiple fingers the experimenter said, "Use your tapping finger, like this" showing them how to do the action properly. Mis-hits were noted on observation notes by research assistants and cross-checked on recorded videos when available.

If the child was very inhibited and needed the parent to sit next to them, the parent was asked to sit slightly to the back of the child.

For each task played, a participant file was exported at the end. All participant files were merged and exported to a *.csv* file using E-Prime software tools. Subsequent preparation steps were done in MATLAB to obtain outcome average measures (described below for each task).

Delayed alternation, indexing WM

This task started with an image on the screen with 2 green doors positioned to the left and right side of an image of a television. The experimenter introduced the task by saying: “Now we’re going to play a game. Behind these doors is a funny man who wants to show us some cartoons. Let’s find him!”. The experimenter started the first trial with her index finger pointing towards the centre of the screen and slowly moved it to the correct door (always to the right-hand side for the first demonstration trial) and said, “I think he’s here.”. She then tapped the door, and the presentation followed a reward sequence, a stop-motion animation of a Lego figure coming out from the door and turning on a television, which then displayed a 7 seconds *Peppa Pig* animated sequence (total reward sequence of 10 seconds) – see Figure 5. 2. The target door alternated on each trial. During 3 more demonstration-and-reward trials only the experimenter touched the monitor, always starting with her finger pointing to the centre of the screen. At the end of the fourth reward sequence, the experimenter said: “Now it’s your turn. Can you find the funny man?”. After the child tapped a door, if correct (opposite door to the previous trial) the experimenter said, “Yay, you found him!” and the reward sequence was played; if incorrect she said, “Oh no, he’s not there.”. If the incorrect door was chosen, a boring sequence was displayed of an animation of the tapped door opening and showing to be empty and a blue screen displayed for 7 seconds (total sequence of 10 seconds). The sequence duration (7 seconds) served both as a reward (if correct) and as a distractor (the child’s eyes were drawn to the centre of the screen so that they would not use gaze to maintain a representation of which door to tap). The duration of the sequence and number of trials were implemented after Hendry (2018) and other studies with this task (Espy et al., 1999; Wiebe et al., 2008). The task took approximately 5 minutes to complete. Throughout the task the reward cartoon was only played by tapping the location opposite from the child’s last correct response, so to achieve the maximum correct score, the child had to alternate tapping between right and left doors on each successive trial. The experiment continued until 23 trials were done (4 demonstration and 19 testing trials), or until the child made more than 10 errors (this happened to one child).

If the child needed encouragement to choose a door, the experimenter prompted by saying, “Where has the funny man gone…which door?”, or “Can you find the funny man? He wants to show you some cartoons”.

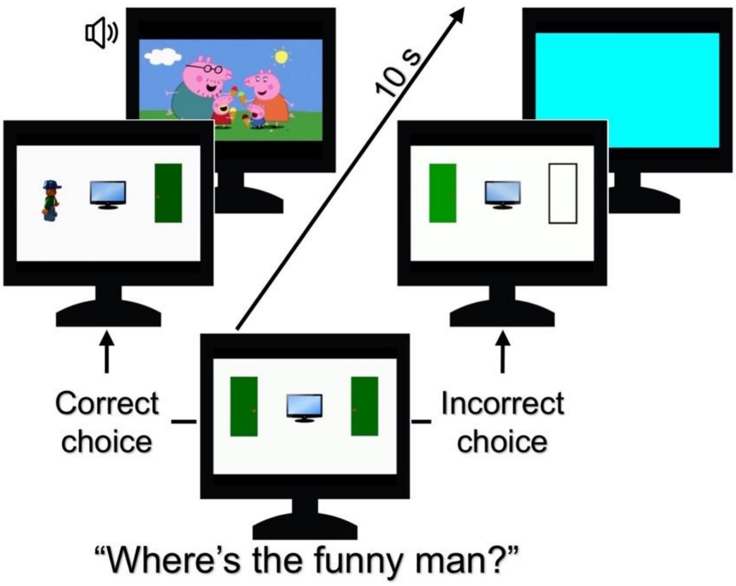

Figure 5. 2. Scheme of the touchscreen-based Delayed Alternation Task. In this example, the correct response was a tap on the door on the left-hand side of the screen.

All children completed the task. Videos of the child playing were watched by a Psychology undergraduate student, blind to group status, to screen for invalid trials – i.e. trials where the child made two choices[10] (13 trials), where the child accidentally tapped a door (1 trial), or where the parent confirmed an answer (1 trial). For 20 children (43%) where video was not available the online observations recorded during testing by the research assistant were used to screen invalid trials. Further trials were excluded based on the time it took the child to choose a side, i.e. if it was more than 23.349 s (3STD of all RT values, total of 9 trials). The dependent measure was computed as the number of consecutive correct trials in the longest run of alternations minus the number of trials in the longest perseverative run (possible range -11 to 19), as an index of working memory as it represents children’s ability to maintain the task demands (maintenance and updating) over the course of task administration (Hendry, 2018; Wiebe et al., 2008) and has been shown to correlate with other measures of working memory (Espy et al., 1999; Stahl & Pry, 2005). A higher value on this score represents a better maintenance of task demands.

In one case there was a technical problem with the task presentation so that the task was terminated after 3 testing trials. The task was restarted from the beginning (trial 1 of demonstration phase) and the child resumed to play straightaway. So, in total this child played 26 trials (including the 3 trials before termination), but only the last 19 trials of the second time task were considered for analysis.

[10] either by tapping the screen with two hands (9 trials), or by first responding to one door (response not registered by the touchscreen monitor) and changing their choice (4 trials)

Three children interfered during the demonstration phase by abruptly tapping one door. In one case the choice was correct and the task continued as normal. In two cases the choice was incorrect and this led to the number of testing trials being reduced to 16 in one case and 17 in another.

One child was very resistant to make a choice and used the parent's finger to tap the screen for 5 consecutive trials. These trials were included in the analysis.

Go/No-go ("Splat the cat!"), indexing cool-IC

The experimenter started this task by saying "Now we're going to play a game called 'Splat the cat'. I'll show you how to play. Ready?" and tapped the screen to launch the task as soon as the child was looking. She demonstrated the task by saying "We have to splat the cat, like this", while she forcefully tapped the screen where a picture of a cat was presented (*Go* trial). She repeated this behaviour twice by saying "Again! We splat the cat", and "We splat the cat as fast as we can". At the fourth trial (where a picture of a dog was presented, *No-go* trial) she said, "But we do not splat the dog" while wagging her finger and shaking her head, and repeated, "No, we don't splat the dog". After a short pause, an interstitial screen appeared. The experimenter said "Now it's your turn to splat the cat, but don't splat the dog. Are you ready?". For four practice trials (fixed order of cat-cat-dog-cat) the experimenter encouraged the child to forcefully splat the cat by reinforcing responses. In the end, another interstitial screen appeared and the experimenter said "Now it's your turn. Remember to splat the cat as fast as you can, but don't splat the dog. Are you ready?". When the child had indicated that they were ready the experimenter tapped the screen and then withdraw to the back of the child's chair. During the testing period, each trial consisted of the presentation of either a cat (18 *Go* trials, 75%) or a dog (6 *No-go* trials, 25%) in a randomized order. Trial number were unbalanced between conditions so that *Go* trials were more frequent and thus elicited prepotent motor activity (*Go* response). The experimenter did not reinforce or correct any responses, unless there had been an obvious mis-hit (child has tried to splat the cat but touchscreen did not register), or if the child needed encouragement to continue – in these case the experimenter said "Remember to splat the cat as fast as you can" or "Keep going" or "The cat is running away!" or "We need to splat the cat".

In both *Go* and *No-go* trials, the relevant stimulus was presented for 1.5 seconds or until the screen was tapped. In *Go* trials, if the screen was successfully tapped before 1.5 seconds an animation (of 2 seconds) of a colourful paint splashed the screen where the cat was with an accompanying sound of a *splash*; in *No-go* trials, if the screen was correctly not tapped before 1.5 seconds the stimuli remained presented on the screen with an accompanying sound of a dog barking – see Figure 5. 3. In both trials, if incorrect, a blank screen was displayed for the same duration.

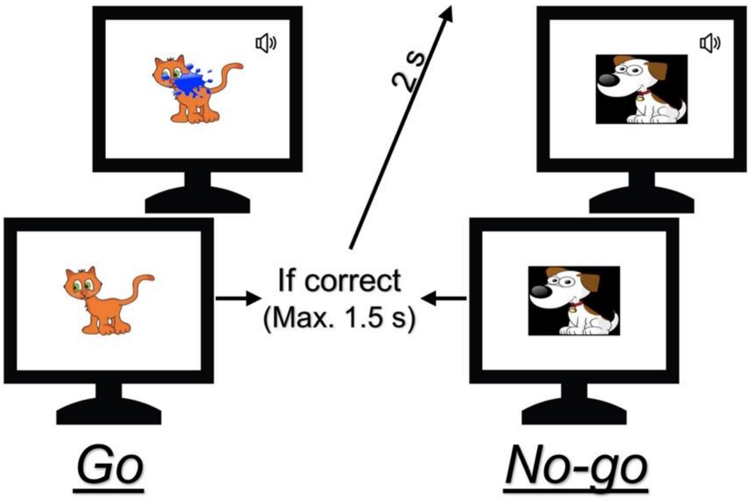

Figure 5. 3. Scheme of the touchscreen-based Go/No-go Task. A correct response in Go-trials is a tap within 1.5 seconds; a correct response in No-go-trials is no tapping within 1.5 seconds. If incorrect, a blank screen would be presented for 2 seconds.

After this testing block finished a switching block started where the same procedure was done as before but with the change that the dog was now the *Go* stimuli. This block was not considered for the measures presented in this thesis. The entire task (demonstration, practice, testing, and switching blocks) took approximately 5 minutes to complete.

All children were invited to complete the task, but three children refused to complete it after the practice period. Videos of the child playing were watched by a Psychology undergraduate student, blind to group status, to screen for invalid trials – i.e. if the child was not looking or away from the seat (74 trials), or if the parent reinforced the game rules during the trial (1 trial). In addition, trials where the child splatted the screen (while the stimuli was still being presented) but the response was not registered by the touchscreen monitor were recoded and included in the errors counts (trials were added as commission errors when answer was not recognised on *No-go* trials and subtracted from omission errors when answer was not recognised on *Go* trials). These unregistered responses (48 trials) were included based on the reason that incorrect splatting might not have been registered due to the impulsive way of tapping the screen but were important to be captured.

For 12 children (26%) where video was not available online observations (recorded during testing) provided by the research assistant were used to screen trials. For five children there were no online testing notes or videos available to screen for trial validity, so these cases were excluded from further analysis. Two dependent measures were computed as the proportion of errors in *No-go* trials (= commission errors, which represent a failure to inhibit responding to *No-go* stimuli) and the proportion of errors in *Go*-trials (= omission errors, which represent a failure to respond to *Go* stimuli and is related to sustained attention in order to keep efficient activation-inhibition during to the task).

5.2.4.2. Measures of EF – table-top tasks

The table-top tasks were done on a child-size table placed in the middle of the room, inside a blue square rug. The child was encouraged to sit at a child-size chair with their back to the couch where parents were seated, and facing the experimenter, who sat on her knees.

Spin the pots, indexing WM

This multi-location search task followed the procedure previously described in (Hughes, 1998; Hughes & Dunn, 1998; Hughes & Ensor, 2005), and previously shown to be a valid and age appropriate measure of working memory (Frick, Bohlin, Hedqvist, & Brocki, 2018; Hughes & Ensor, 2005). It started with the experimenter encouraging the child to play with her a "treasure hunt" game: "We're going to play a game that's lots of fun, and you can win some treasure". Then the experimenter put upon the table eight visually distinct pots on top of a rotating tray (Ø 39 cm). While the child was watching, the experimenter opened each of the pots and started to hide craft gems (assorted size from 10 mm to 25 mm) inside each pot. She said, "Now, I'll hide some treasure in the pots, like this". A gem was put in all but a pink and a green pot (always positioned opposite each other in the tray array), and the experimenter said "We don't have enough gems for all the pots, so these two pots are empty" while the empty pots were shown to the child and closed. She continued by saying: "Now I'll cover it up like this [and placed a black opaque scarf over the tray]. Now, we're going to spin the tray, and I want you to choose a pot. Now, can you pick a pot to find some treasure? Show me which pot you want to open." – see Figure 5. 4. Only once the child had picked and opened a pot, and retrieved or not a gem, the empty pot was put back onto the tray, as was the scarf, and the tray was again spun. This procedure was repeated until all treasures were found, or for a maximum of 16 trials. The task took approximately 5 minutes to complete.

If the child needed encouragement to choose a pot the experimenter prompted again until they picked one and opened it. If the child started picking up a pot and suddenly changed his mind to another pot the experimenter redirected them to pick the first chosen pot (the movement to the first pot might have given the child feedback of whether the pot was empty or not). If the child picked a pot and put it back without opening it, but after shaking it and realising it was empty, the trial was considered an incorrect choice and the tray was spun around again. If the child picked up two pots at the same time, the trial was considered an incorrect choice.

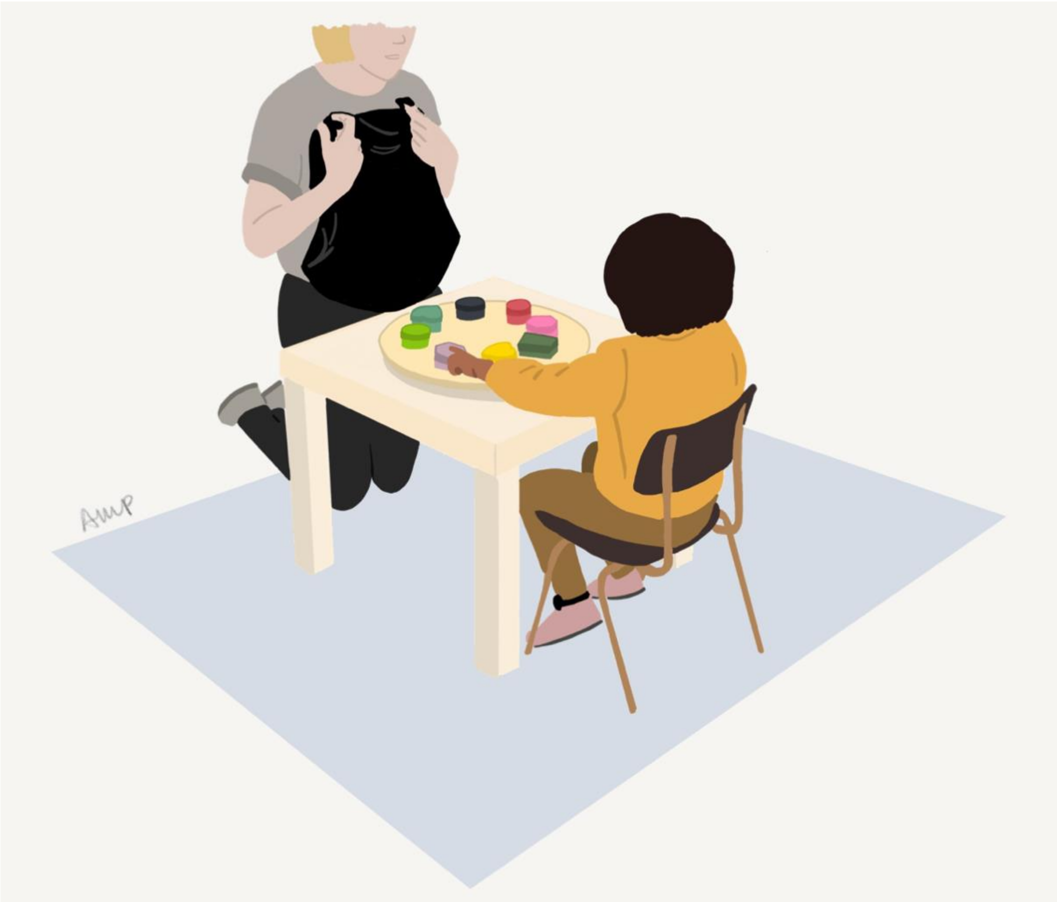

Figure 5. 4. Illustration of a child doing the Spin the Pots task.

All children completed the task. The data was coded from video by a Psychology undergraduate student, blind to group status, except for 4 children (9%) where video was not available – in these cases the online rating (scored during testing) provided by the research assistant was used. The dependent measure was calculated as the total number of possible trials minus the number of unsuccessful trials (possible range 0 to 16). The most successful performance (maximum score = 16) is achieved if all treasures are found in as few trials as possible (while maintaining and updating which pots were opened in working memory).

One child asked for a toilet break just before finishing the task, after 8 trials and 5 gems found. After coming back, this child found the last gem. This means that this child score is the same, whether or not the trial after the break is considered.

Snack delay, indexing hot-IC

This was a delayed gratification task adapted from Kochanska and colleagues (1996; 2000). The task was introduced as an occasion for the child to get a treat (a paw-shaped dried fruit). The experimenter set up on the table a placemat decorated with two handprints, a transparent cup, and a bell – see Figure 5. 5. After the experimenter placed a treat under the cup the child was instructed to stand still with their hands on the mat until she rang a bell signalling the end of the task: “Now, I’ll place the *bear paw* here, and you have to wait for me to ring this bell before getting the treat. Ready?”. Four trials were done with delays of 10 s, 20 s, 30 s, and 240 s. Halfway through the delay, the experimenter lifted the bell but did not ring it. The experimenter restated the rule before each trial. Only one treat was placed under the cup for the first three trials, and three treats were placed on the fourth trial. During this last trial, the experimenter initiated a series of distractions (i.e., coughing, writing), and after she lifted the bell (but did not ring it) she left the room for a period of 90 s, and resumed the task when came back. The task took approximately 7 minutes to complete.

Figure 5. 5. Illustration of a child doing the Snack delay task.

All children completed the task. For two cases, an alternative treat was used (in one case bear-shaped savoury potato snacks and in the other mini gingerbread men biscuits).

Performance was coded as a trial score ranging from 0 to 6 (0 = child ate the treat before the bell was lifted, 1 = ate the treat after the bell was lifted, 2 = touched the bell or cup before the bell was lifted, 3 = touched the bell or cup after the bell was lifted, 4 = removed both hands from the mat before the bell was lifted, 5 = removed both hands from the mat after the bell was lifted, and 6 = waited for the bell to ring). In the case instructions to keep hands on the map were not clearly given by the experimenter (this happened for 4 trials), the maximum score was given unless the child had touched the glass/cup. The data was coded from a video by a Psychology undergraduate student, blind to group status, except for 1 child where video was not available – in this case, the online rating, scored during testing by the research assistant, was used. This online rating did not include the hands code, so the child was given the maximum score possible accordingly. The dependent measure was a sum score of all trials to index the ability to delay gratification (possible range 0 to 24). Inter-rater reliability between the video coding was 0.992 (95% CI: 0.969 - 0.998, n = 10) assessed using a single measures 2-way mixed model.

Dimensional Change Card Sorting (DCCS), indexing CF

This task followed the procedure (standard version) described by (Zelazo, 2006), where children are required to sort a series of bivalent test cards, first according to one dimension (e.g. color), and then according to the other (shape). The experimenter, sat 90 degrees to the child, set up two sorting trays (wooden boxes, 14 x 5 x 9 cm) within reaching distance from the child, each with a target card on display (a blue rabbit on the tray on child's left and a red boat on the tray on the child's right), as illustrated in Figure 5. 6. The experimenter started by labelling the target cards by both dimensions "Here's a blue rabbit and here's a red boat.". She continued saying, "We're going to play a cards game. It's the colour game. In the colour game, all the blue cards go here [pointing to the tray on the left], and all the red cards go there [pointing to the tray on the right]". The experimenter then sorted one type of test card while reinforcing the rule. She then asked the child to sort a card: "Now here's a red one. Where does this one go?". If the child sorted the card correctly the experimenter said, "Very good. You know how to play the colour game"; if the child sorted incorrectly, the experimenter said, "No, this one's red, so it has to go over here in the colour game. Can you help me put this red one down?". In any case, the experimenter ensured that the card was placed face down in the appropriate tray, instructing the child to do so and turning the card over if necessary.

The experimenter then started the pre-switch phase. On each pre-switch trial (6 in total) the experimenter showed a card to the child and labelled it by the relevant dimension, “Here’s a red one. Where does it go?”. Whether or not children sorted correctly, the experimenter simply said, “Let’s do another one”, and proceed to the next trial.

Figure 5. 6. Illustration of a child doing the DCCS task.

At the end of the last pre-switch trial, the experimenter said, “Well done. You know how to play the colour game. Now, we’re going to play a new game. We’re going to play the shape game. In the shape game, all the rabbits go here [pointing to the tray on the left with a rabbit], and all the boats go there [pointing to the tray on the right with a boat]. Remember, if it’s a rabbit, put it here, but if it’s a boat put it there. Ready?”. On the post-switch phase the experimenter did not remove the target cards or the cards that were sorted during the pre-switch phase. For each post-switch trial (6 in total) the experimenter showed the card to the child, labelled it by the relevant dimension only, and asked, “Where does this one go?”. Whether or not the child sorted the card correctly, the experimenter simply said, “Let’s do another one”, and proceed to the next trial. The complete task took approximately 1.5 minutes to complete.On each trial, when selecting a test card the experimenter ensured that the same type of test card was not selected on more than two consecutive trials. The relevant dimension on the pre-switch phase was counter balanced between touchscreen use groups.

All children completed the task. All children sorted correctly all pre-switch trials. Successful performance on the post-switch phase of the DCCS is an index of cognitive flexibility. For each trial, children's final response was scored as either a correct or incorrect choice. The data was coded from a video by a Psychology undergraduate student, blind to group status, except for 5 children (11%) where video was not available – in these cases the online rating provided by the research assistant was used.

Glitter wand, indexing IC

This was a Prohibition Task similar to the one described in Friedman, Miyake, Robinson, and Hewitt (2011) study. The experimenter, sat opposite to the child, drew the child's attention to an attractive toy (a glitter wand), placed it on the table within reach of the child, and said: "Look! Wait, don't touch it yet" while shaking her head, and then looked down to the wand – see Figure 5. 7. The trial continued for a maximum of 30 s, starting from the end of the experimenter's instruction until the child touched the wand or the trial ended. At the end of the trial, the experimenter released the prohibition by saying "You can touch it now", prompting again after 5 s if the child had not touched it.

Figure 5. 7. Illustration of a child doing the Glitter Wand task.

All children completed the task. Performance was coded dichotomously as a function of whether the wand was touched, i.e. children were classified in 1 of 2 groups: high control (if child did not touch the wand before the trial ended) and low control (if child touched the wand before the trial ended). This decision was based on previous reports that the distribution of the delay to touch the wand follows a bimodal distribution at this age, i.e. children either touch the wand very soon after instructions or they do not touch the wand at all. The data were coded from video by a Psychology undergraduate student, blind to group status, except for 4 children (9%) where video was not available – in these cases the online ratings provided by the research assistant were used.

5.2.4.3. Measures of EF – the Anti-saccade task

The gaze-contingent Anti-saccade task has been described extensively in Chapter 4, where I investigated the longitudinal associations of touchscreen use and look behaviour and saccadic latencies on this task, with data collected across all lab visits. Anti-saccade behaviour is considered to be an index of inhibitory mechanisms and it is thought to demand executive and prefrontal type processes (Coe & Munoz, 2017; Munoz & Everling, 2004; Roberts, Hager, & Heron, 1994). For that reason, in the current chapter, I am using anti-saccade behaviour data collected at 3.5 years as an additional index of inhibitory control.

As mentioned in Chapter 2 and 4, this task was administered using an eye-tracker (Tobii TX300) system and after another block of eye-movements tasks, so children were seated on their parent’s lap when the task initiated (except for 6 children who did the task sited on the chair by themselves). The task was introduced to the child as an entertainment by saying “We’re going to watch some jungle animals on the *TV* now”. The task was played automatically, based on the participant’s eye-movements. In the task, participants must suppress the reflexive response of looking at a visual distractor that appears suddenly on one side of the screen (pro-saccade) and must instead look away, in the opposite direction, where a target stimuli is going to be presented (= anti-saccade). This behaviour is reinforced by rewarding children to look at the target location with an animation (spinning and sound) of a jungle animal. See the full description of procedure and gaze processing steps is in Chapter 4.

Because children need to learn the anti-saccade behaviour during the task, the outcome measure was the proportion of anti-saccade in the second half of the task.

Data from 2 children was not collected due to technical problems and refusal to take part. All other children yielded enough valid trials to be included in this analysis (number of valid trials on the task higher than 5).

5.2.4.4. Measures of EF – parent-report: Child Behaviour Checklist

Parents completed the CBQ short-form (Putnam and Rothbart, 2010), a 94-item measure of childhood temperament, as part of the online questionnaire they were invited to fill prior to the lab visit. In addition, 15 items from the standard CBQ (Rothbart, Ahadi, Hershey, & Fisher, 2001) were added to the questionnaire, in order to have complete measures for three scales relevant to the project (inhibitory control, attention focusing, and attention shifting) but not to burden the parent. On the CBQ, parents are asked to report on how often during the preceding 6 months their child demonstrated certain behaviours related to each scale the questionnaire measures. All scales use a 7-level Likert response format (ranging from ‘Extremely untrue’ to ‘Extremely true’); with an additional ‘not applicable’ field that the parent is instructed to tick only if they have not seen the child in the situation the question portrays. Mean scores were calculated for each subscale. Parents filled this questionnaire online prior to attending the lab visit, except for 6 parents who filled the questionnaire in the lab, while their children were doing the EF battery tasks. For two cases, the parents did not fill the questionnaire because they did not get the time to fill it during the session and were not available to fill it after at home.

Parent-measures may provide important information on individual differences beyond that captured in laboratory measures (Joyce et al., 2016). However, parent-reported measures are biased and often correlated between themselves. For this later reason, only the Inhibitory Control scale (13 items, indexing child’s ability to stop, moderate, or refrain from a behaviour under instruction) was included for the EF analysis described below.

5.2.5. Analytical approach

Data preparation

All cases highlighted above (e.g. the three cases where order of the tasks was reversed) were flagged, but not excluded from the main analysis because, 1) some of these cases might provide important variation in EF performance, 2) the main analysis makes use of a composite measure (see below) where unusual performance in one task is going to be dissipated by the other tasks’ performance. Before conducting the analyses described below, the data were visually and statistically examined to flag outliers, skew distributions, and floor or ceiling effects.

- *Delayed alternation*: one child had a WM (maintenance) score of 3SD above the mean – this was the case of a child who performed exceptionally well in the task (did not do a single error), but seemed to be a valid performance a decision was made to keep it in the dataset.
- *Go/No-Go*: the proportion of commission errors (incorrect *No-go* trials) showed floor effects with 29 children out of 38 (76%) making no such errors at all. No child performed at ceiling. This measure was recoded as a dichotomous variable, where children were classified to 1 of 2 groups: inhibiters (proportion of commission errors was 0) or failed to inhibit (proportion of commission errors was higher than 0). There were no outliers in the distribution of proportion of omission errors.
- *Spin the pots*: there were no outliers in the distribution.
- *Snack Delay:* one child had a sum score of 4SD below the mean – because there was no other reason to consider this case invalid and the score seemed a reflection of the child's behaviour on this task, a decision was made to keep this score in the dataset.
- *DCCS*: performance (number of cards sorted correctly) on the post-switch phase showed a broadly bimodal distribution (only 4 children had a score different than 0/ none correct or 1/ all correct). This is in line with the literature on the task (Zelazo, 2006), therefore, children were classified to 1 of 2 groups: switchers (sorted at least five post-switch trials correctly) or failed to switch (failed to sort at least five cards correctly), and the task analysed as categorical data.
- *Glitter Wand*: most children in the sample seemed to have high control in this task, with only 7 children out of 46 (15%) failing to inhibit touching the wand before the experimenter said so.
- *Anti-saccade Task:* the proportion of anti-saccades done at the second half of the task ranged from 0 to 1, with 15 children (34%) not doing any anti-saccades.

Pre-registration

As already mentioned throughout this thesis, the 3.5 years visit analysis plan was pre-registered prior to data processing[11]. Touchscreen group differences in executive function measures at 3.5 years were proposed to be tested separately for the screen-based tasks (Delayed Alternation, Go/No-go, Switch) and the real-world tasks (Spin the pots, Snack Delay, DCCS), using a multivariate analysis of variance (MANOVA) statistical

[11] https://osf.io/fxu7y

approach with each task index as dependent variables, and usage group as fixed factor. However, due to the varied type and distributional properties of the data, and the modest sample size of the study, this approach was not appropriate.

- In the case of the screen-based tasks, the Go/No-go Task had several participants that did not perform the task/ did not provide data for technical reasons, and thus could not be included in a MANOVA, although they had valid data on other measures. During the pre-registration, the outcome measure from this task was intended to be a D' measure, which summarises the hit rate (proportion of omission errors subtracted from 1) and the false alarm rate (proportion of commission errors) and is said to be a sensitivity measure of task performance. However, given the distributional properties of the two types of errors, and the constructs they intend to measure, it was decided to keep both measures separate. An additional obstacle for the implementation of the planned analysis was that one of the measures that was planned to be included in the MANOVA (the measure obtained with the Switch Task, indexing CF) was ignored for the current analysis, given that it has not been yet validated.
- In the case of the table-top tasks, both the Spin the pots and the Snack delay tasks provided continuous measures, but the DCCS task measure, as reported before, had a bimodal distribution, and therefore could not be included in a MANOVA.

For these reasons, another analytical approach (see below, exploratory and confirmatory factor analysis) was chosen which makes use of all available data points for each participant, and accounts for the different data types present and for Type 1 error (multiple comparisons). Yet, to fulfil the pre-registration intentions, univariate comparisons were computed for each measure data with a test appropriate to each and with touchscreen usage group as a factor, and these will be reported in a separate section. For these comparisons, non-normally distributed data (tested for normality with Shapiro-Wilk test, $p > 0.05$) was transformed (using square root transformation) and tested using a t-test; if transformation did not work (again, tested with Shapiro-Wilk test, $p > 0.05$), a non-parametric test was used (Mann-Whitney test); and categorical data was tested using a Chi-Square.

The hypotheses on this pre-registration plan were non-directional, i.e. given conflicting literature in regards to traditional media platforms (television and video-games) it was predicted that high and low users would differ in EF but no prediction about the direction of such effect was expressed. Because new evidence was published since then, which suggests that touchscreen media use might be associated with reduced EF

(McNeill et al., 2019), the predictions changed accordingly. It was predicted that high users of touchscreens would show poorer performance on the EF measures.

Data reduction – exploratory and confirmatory factor analysis

Given the multitude of measures of EF incorporated in this study and the mixed nature of data types (which does not allow the use of straightforward composite measures), a data-driven analytic method (exploratory factor analyses, EFA) was preferred to first study the underlying latent structure on this sample; with a subsequent confirmatory factor analysis (CFA), based on the pattern found and theoretical interpretation, to test the associations with touchscreen media use. The MPlus latent variable framework (MPlus version 8; Muthen & Muthen, 2017) was used to run the models.

First, an EFA was run with the outcome measures described above. Variables were re-scaled before being entered in the analysis so they would range approximately 0 to 1. To accommodate the use of some categorical indicators and normally and non-normally distributed continuous variables, and to allow all available data to be included in the model, a mean- and variance-weighted least squares estimator (WLSMV; Asparouhov & Muthen, 2010) was used. Eigen values and corresponding scree plot were inspected to inform the adequate number of factors, and fitness for this factor solution was examined based on a non-significant chi-square statistics, a root-mean-square error of approximation (RMSEA) of < 0.05, and a comparative fit index (CFI) of > 0.95 (Hu & Bentler, 1999). Factor loadings > 0.3 were interpreted.

Next, a model based on the factor solution was specified using a CFA, with factors regressed on touchscreen media group. The CFA, a structural equation modelling (SEM) technique, is a theory-driven approach to assess model validity. Because it extracts common variance from measures, and different measures of the same EF component were included (measures that are known to be susceptible to the task impurity problem) the resultant latent variable is assumed to be a purer measure of its construct. In structural equation modelling (i.e. the CFA model), a minimum of 3 items (i.e. observed measures) per latent construct (i.e. factor) is generally required. Although it is possible to use 2 items if all the latent constructs correlated with each other, due to the modest sample size, the most conservative route was followed. In this study, the CFA approach was used to examine both the EF structure model fit and touchscreen group effects. EF factors were created by loading the observed measures, selected based on their loadings in the EFA (i.e. > 0.3), and fixing the first factor loading at 1. In Model 1a, touchscreen usage group at 3.5 years was used as predictor of these factors to test whether Touchscreen use would be associated with EF. Model 1b included Background TV as a predictor of EF scores to assess the specificity of the effects to touchscreen usage. The CFA model was also evaluated using the three criteria aforementioned: non-significant chi-square statistics; a RMSEA of < 0.05; and a CFI of > 0.95. Standardised model estimates (STDYX) are reported throughout.

Follow-up analysis

Given that it is generally recommended to have large sample sizes for SEM analysis, and the modest sample size of this study, the analysis in this chapter was limited to testing the associations with concurrent touchscreen media use. However, to test the associations with longitudinal touchscreen use, and assess the specificity of findings to recent or prolonged touchscreen use, the measure loading most strongly onto each latent factor was used as independent variable in follow-up regression analyses.

5.3. Results

5.3.1. Exploratory factor analysis

EF measures described in the the section 5.2 ‘Method’ and presented in Table 5. 1 were included in an Exploratory Factor Analysis (EFA) with the primary purpose of identifying EF latent constructs underlying the 3.5 years sample on EF performance.

Table 5. 1. Performance on EF measures at 3.5 years.

Continuous Measures	**N**	**M (SD)**	**Raw range**	**% Ceiling**
Delayed Alternation WM Score	46	0.55 (0.44)	-4 – 19	2%
Spin the pots Score	46	1.19 (0.33)	5 – 16	13%
Go/No-Go % Omission Errors	38	0.16 (0.14)	0.00 – 0.57	13%
Anti-saccade % 2^{nd} Half	44	0.39 (0.35)	0.00 – 1.00	7%
Snack Delay Sum Score	46	2.13 (0.28)	10 – 24	24%
CBQ Inhibitory Control Score	45	0.47 (0.09)	2.00 – 5.92	2%
Categorical measures	**N**	**%**	**Count**	
Go/No-Go High Control	38	0.76	29	
DCCS Switchers	46	0.59	27	
Glitter Wand High Control	46	0.85	39	

Geomin (oblique) rotated solutions for one, two and three factors were examined for the factor loading matrix – a solution of 4 factors was not appropriate in this study considering the criteria for the CFA of a minimum of 3 items loading in each construct. The three factor solution was chosen for three reasons: 1) the initial eigen values above 1, the scree plot in Figure 5. 8, and the good model fit; 2) its interpretability according to the EF organization theoretical background (i.e. EF as a set of separate skills: WM, IC, and CF); 3) the discrepancy in the two factor solution in terms of the direction of item loadings (i.e. the DCCS was loading in the opposite direction with the other measures in factor 1), see Appendix 5a.

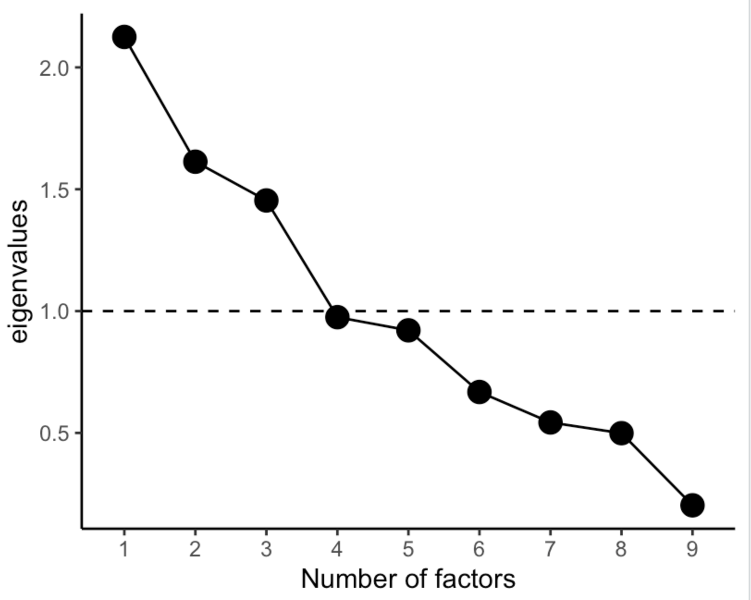

Figure 5. 8. Scree plot for the EFA with EF measures.

Each of the tasks included in the task battery were assumed (but not imposed in the model) to be unidimensional (i.e. their measures index a single ability, e.g. the DCCS measures cognitive flexibility). Therefore, it was expected that tasks which tapped the same ability to load together onto separate factors representing the underlying EF ability (i.e. working memory, cognitive flexibility, and inhibitory control). However, the data from this sample at 3.5 years did not support this tri-dimensional organisation, as seen by observing the factor loadings matrix for each observed variable in Table 5. 4. However, in light of the current debate in the literature about how EF is structured in early development (Fiske & Holmboe, 2019; Hendry et al., 2016) and with the Hendry et al. conceptual model in mind (see again Figure 1. 2), the results of the EFA suggest that performance in the EF battery could be reduced to three factors that tap the three proposed emergent EF abilities:

- Factor 1 which I will label IC, *cool* Inhibitory Control or active response inhibition, and that in Hendry's conceptual model of EF in toddlerhood is denoted as Resolving Conflict (in this case, between dominant and sub-dominant motor responses), measured by the Go/No-go and Anti-saccade Tasks;
- Factor 2 which I will label DG, Delayed Gratification, which is denoted as Impulse Control in the model, and is measured by the Snack Delay and the Glitter Wand, both delay of gratification *hot*-EF tasks;

- Factor 3 which I will label CF, Cognitive Flexibility, which is denoted by this name in the model, but is related to both cognitive flexibility (shifting) and to working memory (maintaining and updating), measured by the Delayed Alternation, Spin the pots, and the DCCS.

The CBQ Inhibitory Control Score did not load to any factor.

Table 5. 2. Factor loadings on each latent construct based on exploratory factor analysis with 3 factors solution and 8 observed variables from the EF battery of the 3.5 years TABLET visit (N=46).

	Factors		
	1. Inhibitory Control	2. Delayed Gratification	3. Cognitive Flexibility
Delayed Alternation WM Score			0.76
Spin the pots Score			0.38
DCCS Switchers			0.59
Go/No-Go % Omission Errors	0.41		
Go/No-Go Low Control	1.07[12]		
Anti-saccade % 2nd Half	-0.31		
Snack Delay Sum Score		0.69	
Glitter Wand High Control		0.80	
CBQ Inhibitory Control Score			

**Factor loadings ≤.3 are supressed.*
Method of extraction = WLSMV, Type of rotation = oblique.
$\chi 2$ (12) = 4.790, p = 0.96; RMSEA < 0.001; CFI = 1.

5.3.2. *Touchscreen group comparisons with confirmatory factor analysis*

Based on the EFA results, a CFA model was run to test the associations between two EF factors – CF measured by Delayed Alternation WM score (factor marking), Spin the pots score, and DCCS Switchers; IC measured by % Anti-saccades (factor marking), Go/No-go % Omission errors, and Go/No-go Low Control; CF correlated with IC – and touchscreen use group. The DG factor was dropped because it did not meet the criteria of having at least three measures loading into the factor, but performance on the measures that underlie this factor (Glitter Wand High control and Snack Delay Sum Score) will be analysed separately.

The CFA model provided a good fit to the data, $\chi^2(12) = 8.174$, $p = 0.771$; RMSEA < 0.001 (90% CI = 0-0.104); CFI = 1. For the Cognitive Flexibility factor, all standardised factor loadings were significant. For the Inhibitory Control factor, factor loadings for Go/No-go measures were significant, and the Anti-saccade measure was marginally

[12] *Factor loading estimations greater than one can occur when factors are correlated (i.e when oblique rotation is used). However, it can also be indicative of a small sample size or a model misspecification, such as too many factors for number of items. Given that the three-factor solution fits the theory best and the factors are interpretable, a decision was made to proceed with this solution to inform the CFA model specification.*

significant. The two EF factors were not correlated. Touchscreen user group was significantly associated with Cognitive Flexibility and Inhibitory Control, with high use of touchscreens at 3.5 years associated with reduced scores. Table 5. 3 shows the standardised beta coefficients and corresponding *p*-values.

Table 5. 3. Summary of the standardized beta coefficient with their p-values for Model 1a: 2-Factor Confirmatory Model of EF with touchscreen group as predictor. The sample included 46 children (27 HUs).

	Standardized Beta, *p* value
Cognitive Flexibility (CF) measured by	
Delayed Alternation WM Score	0.601, 0.005
Spin the pots Score	0.370, 0.038
DCCS Switchers	0.706, 0.011
Inhibitory Control (IC) measured by	
Anti-saccade % 2^{nd} Half	0.389, 0.075
Go/No-Go Low Control	-0.839, 0.001
Go/No-Go % Omission Errors	-0.416, 0.034
CF on user group	-0.429, 0.031
IC on user group	-0.430, 0.021
CC with IC	-0.117, 0.677

In a second model (Model 1b), the previous CFA model was re-run controlling for concurrent Background TV. Model fit was good: $\chi 2(16) = 11.511$, $p = 0.777$; CFI < 0.001 (90% CI = 0-0.095); RMSEA = 0. Factor loadings and the correlation between factors were generally unchanged – except for the Inhibitory Control factor, where the factor loading for Go/No-go Omission Errors measure became marginally significant, and the Anti-saccade measure became significant. In terms of the media use associations for the Cognitive Flexibility factor score, the significant association with touchscreen use group became marginal, but there was no association with concurrent Background TV; for the Inhibitory Control factor score, the effect of touchscreen use group became nonsignificant, while concurrent higher Background TV was significantly associated with a lower score. See the standardised beta coefficients and corresponding p-values in Table 5. 4.

Table 5. 4. Summary of the standardized beta coefficient with their p-values for Model 1b: 2-Factor Confirmatory Model of EF with touchscreen use group and Background TV as predictors. The sample included 45 children (26 HUs).

	Standardized Beta, *p* value
Cognitive Flexibility (CF) measured by	
Delayed Alternation WM Score	0.542, 0.007
Spin the pots Score	0.396, 0.036
DCCS Switchers	0.692, 0.012
Inhibitory Control (IC) measured by	
Anti-saccade % 2^{nd} Half	0.473, 0.029
Go/No-Go Low Control	-0.807, 0.001
Go/No-Go % Omission Errors	-0.330, 0.072

	Standardized Beta, *p* value
CF on user group	-0.360, 0.089
CF on Background TV	-0.057, 0.813
IC on user group	-0.328, 0.133
IC on Background TV	-0.472, 0.030
CC with IC	-0.360, 0.265

Longitudinal analysis

Given that daily reported touchscreen use varied along the longitudinal visits (see Chapter 2), the effect on EF was tested to assess if it was specific to the age point when the measures were observed, or whether there were longitudinal associations with touchscreen use across visits. The measure with highest loading in each of the factors on the CFA (the DCCS binary outcome for the CF factor and the Go/No-go control binary outcome for the IC factor) was used to test longitudinal associations with the stable touchscreen group (presented in Chapter 4) in a logistic regression with stepwise selection.

For the measure of Cognitive Flexibility, the DCCS (0 = fail to switch, 1 = switch), a binary logistic regression model with stable use group as predictor (LUs as reference category) showed a marginal significant effect of longitudinal stable use in the model, Wald $\chi2(1) = 3.750$, $p = 0.053$, odds ratio of 4.200 (odds of passing the DCCS are 4.2 times higher for low users). When Background TV (averaged across visits) was added as predictor into the model, the stable group effect become nonsignificant, Wald $\chi2(1) =$ 2.569, $p = 0.109$, and the covariate was also nonsignificant, Wald $\chi2(1) = 0.453$, $p =$ 0.501.

For the measure of Inhibitory Control, the Go/No-go (0 = no commission errors/ high control, 1 = low control), a binary logistic regression model with stable use group as predictor showed that longitudinal stable use was marginally significant in the model, Wald $\chi2(1) = 3.124$, $p = 0.077$, odds ratio of 0.130 (odds of doing commission errors in the Go/No-go are 7.7 times higher for high users). When Background TV (averaged across visits) was added as predictor into the model, the stable group become nonsignificant, Wald $\chi2(1) = 1.778$, $p = 0.182$, and the covariate was marginally significant, Wald $\chi2(1) = 3.800$, $p = 0.051$, odds ratio of 1.007 (odds of doing commission errors increase by a factor of 1.007 for additional minute[13] of average Background TV).

[13] *This is equivalent to an odds ratio of 1.524 for every hour of average Background TV.*

5.3.3. *Multiple comparisons analysis at 3.5 years*

In this subsection, touchscreen usage group multiple comparisons are reported, for each EF measure described in the pre-registration of the 3.5 years assessment and/or included in the EFA analysis reported above, with a univariate test appropriate to each data type and distribution. See results in Table 5. 5 below.

Table 5. 5. Performance statistics and multiple comparison analysis on the EF measures, by touchscreen use group at 3.5 years. All variables index performance on EF in a way that a higher value is better EF, except for Go/No-Go % Omission Errors.

	LUs	HUs	Test statistic	Uncorrected p-value
Touchscreen-based Tasks				
Delayed Alternation WM Score M(SD) n (girls)	6.84 (5.18) 19 (12)	4.63 (3.65) 27 (11)	U = 202, z = -1.224	0.221
Go/No-Go High Control (0/1) % n (girls)	0.88 16 (9)	0.68 22 (9)	$\chi^2(1)$ = 1.913	0.167
Go/No-Go % Omission Errors*: M(SD) n (girls)	0.33 (0.17) 16 (9)	0.36 (0.21) 22 (9)	t(36) = -0.423	0.675
Table-top Tasks				
Spin the pots Score M(SD) n (girls)	12.32 (3.13) 19 (12)	11.59 (3.38) 27 (11)	U = 217.5, z = -0.877	0.381
DCCS Switchers (0/1) % n (girls)	0.58 19 (12)	0.30 27 (11)	$\chi^2(1)$ = 3.675	0.055
Snack Delay Sum Score M(SD) n (girls)	21.05 (3.36) 19 (12)	21.56 (2.34) 27 (11)	U = 271.5, z = 0.339	0.734
Not pre-registered but included in the EFA				
Glitter Wand High control (0/1) % n (girls)	0.84 19 (12)	0.85 27 (11)	$\chi^2(1)$ = 0.008	0.928
Anti-saccade Anti-saccades 2nd Half M(SD) n (girls)	0.50 (0.35) 18 (11)	0.31 (0.34) 26 (10)	U = 158, z = -1.853	0.064
CBQ Inhibitory control M(SD) n (girls)	4.98 (0.97) 18 (12)	4.47 (0.74) 26 (11)	U = 120.5, z = -2.711	0.007

**transformed using a square root transformation, which normalised the score (Shapiro-Wilk test, p=0.071)*

Descriptively, high users had a consistently poorer performance on all EF tasks, except for the Delayed Gratification ones (*hot* IC) which did not differ between groups. The difference between groups performance was marginally significant on the DCCS (which indexes cognitive flexibility), on the Anti-saccade (indexing inhibitory control), and was significant in the parent-report measure of inhibitory control.

5.4. Discussion

The main purpose of this study was to describe the associations between amount of touchscreen use at 3.5 year-olds (indexed by the classification they had in terms of their parent-reported duration of use, above or below the sample median) and their executive function abilities at the same age. This study is unique in that it finds a negative link with cognitive flexibility (CF, including maintaining, updating, and shifting, thus also related to WM) for higher (equal or above the median) levels of touchscreen use; finds a link with inhibitory control (response inhibition of prepotent motor behaviours) not specific to touchscreen use but confounded with other variables related to the media environment (i.e. Background TV in the home), and does not find a link with delay of gratification measures.

Also, this study investigated how EF was organised at 3.5 years in this 46-child sample. Contrary to a tri-dimensional view of EF, where each component of EF is dissociated from each other, the findings in this chapter support a model that dissociates measures tapping cognitive flexibility and working memory (which load into a single factor) from inhibitory control measures related to response inhibition (which load into a second separate factor), and from *hot*-inhibitory-control measures related to delay of gratification (which load into a third separate factor). It is not surprising that WM and CF measures are related at this age: it seems that during the early years there are overlapping stages of development on abilities related to maintaining task set (an abstract representation of a goal or rule), updating task set, and shifting task set; it is this ability of manipulating mental sets in increasing levels of ability that the CF EF Factor score seems to be tapping. The EFA analysis presented above also showed a distinction between measures of inhibitory control, particularly distinguishing IC as measured by delay of gratification tasks and IC measured by pre-potent motor response inhibition tasks. This has also been evident in previous studies (e.g. Carlson & Moses, 2001; Murray & Kochanska, 2002), and contemporary researchers in the field (Munakata et al., 2011) have suggested two types of neural processes sub-serving inhibition – one more related to directed global inhibition (inhibition of overall function in certain brain areas, which I propose the DG EF factor is more related to) and another more related to competitive inhibition (solving conflict between pre-potent responses and task-relevant ones, which I propose the IC EF factor is more related to). Also, it is still unclear in the field whether the same brain systems support inhibition of eye movements and other inhibitory behaviours. It is interesting to observe that the Anti-saccade Task (a measure of oculomotor inhibition) loaded together with the Go/No-go Task outcomes (a more traditional measure of inhibition in the context of EFs), which suggests a shared neural substrate between functions.

This is the first study investigating how EF abilities in pre-school years are related to concurrent touchscreen media use. The present study adds to the field by showing concurrent associations between touchscreen use (indiscriminate in terms of type of use) and EF performance, using a combined data- and theory-driven approach to the study of EF, and showing that 3.5 year old children who had a higher level of touchscreen use performed poorer in a composite measure of cognitive flexibility and working memory. These findings are broadly consistent with previous reports of short-term associations between media use (in those cases, television) and EF. A recent study has provided preliminary evidence of a longitudinal association between active media use and EF, by reporting that app and game play using tablets and other devices at 4 years of age was associated with poorer inhibitory control 1 year later, but reporting lack of evidence for an association with working memory and cognitive flexibility. Furthermore, the results in this chapter suggest, too, a link between touchscreen media use and *cool* IC, but confounded by the family media environment; in contrast, the associations with the EF ability to keep and switch between mental task sets seem specific to touchscreen use.

There are at least three possible explanations for the findings presented. Use of touchscreen devices (i.e. tablets, smartphones, touchscreen computers) might (1) weaken goal or task set representations, and/or (2) create difficulties disengaging from previously learned task set and/or, (3) limit cognitive resources available for EF. These three explanations are not mutually exclusive.

Cognitive flexibility, or the capacity to respond efficiently to new situations (sometimes by generating alternative behaviours), and to engage cognitive control in preparation for when it is needed, rather than only when it is required or prompted by the environment, is very important to improve life outcomes (i.e. is linked to problem-solving, creativity, and adaptive behaviour). But the opposite to cognitive flexibility, i.e. perseveration, can reflect an ability to learn regularities in the world (in the sense that perseveration occurs only when there is a prediction of a regularity in the environment, and that persevering in a response can foster learning of a behaviour) and evidence suggests that top-down goals can actually override the learning of environmental regularities (Thompson-Schill, Ramscar, & Chrysikou, 2009; Werchan & Amso, 2017). This is particularly apparent in bilingualism where children get a less regular linguistic environment and thus appear to develop more flexible thinking (Bialystok, 2015); or in studies with children who experienced adverse childhood environments (characteristic of unpredictable or more chaotic environments) that showed enhanced cognitive shifting performance in uncertain contexts (Mittal, Griskevicius, Simpson, Sung, & Young, 2015). During the fourth year of life there is a transitional shift from perseverative to flexible responding, which is often tapped by the DCCS and partially by working memory measures. This has been presented as a fundamental milestone development in early cognition (Munakata, Snyder, & Chatham, 2012).

Problems with perseveration on the DCCS have been explained by a number of factors, including perceptual conflict and negative priming. This is evident in studies showing that DCCS performance improves dramatically when there is no perceptual conflict between test and target cards (Doebel & Zelazo, 2015; Perner & Lang, 2002; Zelazo et al., 2003), and that post-switch failures are related to difficulties activating the previously-irrelevant-now-relevant dimension (Zelazo et al., 2003) but also to failures in releasing activation of the previously-relevant-now-irrelevant dimensions (negative priming).

One developmental theory of EF that has addressed the DCCS difficulties focused on working memory (Morton & Munakata, 2002), and proposed that the ability to overcome perseveration is related to the development of mental representations of goals: as the ability to actively maintain and update information in working memory develops, the switching on the DCCS occurs when working memory capacity is strong enough to outcompete the latent stimuli-response (S-R) representation formed during the pre-switch phase. Put another way, successful switchers use more abstract active rule representations, while "perseverators" use more stimulus-specific latent representations.

I have shown in previous chapters that high touchscreen users are faster at finding a salient perceptual feature. I have argued that this might be indicative of greater learning of the regularities of stimuli-reward on-screen, and that they might have, in the short-term, a stronger pairing representation between stimuli and responses. I now add that high touchscreen users might have a stronger representation of latent perceptual features and the associations of stimuli and responses, which lead to failures in shifting task set (e.g. in the DCCS the pre-switch S-R representation is stronger), and in updating the task set (e.g. in the delayed alternation task the pairing between the last successful door side and reward is stronger). It would be interesting to investigate whether faster bottom-up attention (indexing stronger stimuli-reward associations) might be related to deficits in CF. Preliminary evidence from the current study does not seem to suggest this association, given that exogenous measures of attention control (i.e. visual single search time) are not associated with performance on the DCCS (see Appendix 5b for preliminary exploratory analysis).

Another developmental theory of EF that has addressed the DCCS difficulties focused on attentional inertia (Kirkham et al., 2003). In this account, children perseverate because they cannot inhibit sufficiently to think of the stimuli in a particular way (i.e. cannot disengage from the pre-switch stimuli-response pairing). Through this account, failures on top-down attention control can be the cause of failures in the DCCS, view which is supported by other studies showing that better selective attention allows inhibition of irrelevant stimuli and increases the activation of relevant stimuli (see Tipper, 2001 for a review). I have shown in the previous chapter that high users of touchscreens struggle with attention disengagement. It would be interesting to investigate whether attention disengagement abilities might relate to cognitive flexibility performance. Preliminary evidence from the current study seems to suggest that endogenous attention control (disengagement in the Gap-overlap Task) at 18 months is related to later performance on the DCCS, but no association is found between concurrent measures (see Appendix 5b).

Another, somehow related, explanation for infants' perseverative errors has been attributed to their limited cognitive capacity. In this view, creation of a strong mental set in EF (necessary for maintaining, updating, and shifting) competes for limited attention resources, and fewer resources are left for EF processes (see Berger, 2004; Thelen et al., 2001). The same idea has been proposed to explain media effects (television) in early years, in a way that television viewing depletes cognitive resources available for EF right after (Lillard, Li, & Boguszewski, 2015b; see Chapter 1). If this is the case for touchscreen use as well, then high users can potentially have limited resources for executive processes, and thus struggle with cognitive flexibility. These limited resources would also compromise performance on IC. However, the effects on this construct seem to be largely unspecific to touchscreen use, and confounded by other environmental factors. It would be interesting to dissociate in future studies the associations of IC with the early childhood media environment, including how different platforms and types of use/ content of programming might contribute to its development.

As it has been highlighted throughout this thesis, the studies presented are simply evidence of a relationship between EF and touchscreen media use, but they do not address the causal direction of this relationship. So, a fourth alternative possible explanation for these findings is that children who struggle with cognitive flexibility are perhaps more predisposed to request and engage with touchscreen technologies, because it provides them with a more regular environment and demand stimulus-specific latent representations (in opposition to active representations that are thought to code for abstract information). Furthermore, their parents may be more likely to use touchscreens as a tool to support their child given their difficulties. This is seen particularly in atypical developmental populations (e.g. Autism Spectrum Disorders, ADHD, which show deficits in EF), where the child's susceptibilities and the parent's strategies to manage their child's behaviour sometimes lead to more screen use (Barkley, 2004).

An important finding in this study was that high and low users of touchscreens did not differ in their IC performance on delay of gratification tasks. This is an interesting finding, particularly in light of the popular concerns about the digital media effects on the developing mind, but one that needs replication from further studies.

The design of this study has many strengths. Firstly, it uses a multitude of traditional and novel EF measures, appropriate for the pre-school age, to capture EF emergent and advanced abilities. Traditional neurocognitive EF tasks adapted to younger children are often confounded by the requirements of other still-developing skills, such as motor control and language skills (Hendry et al., 2016) and require children to internalise and comply with the rules and task goals set by the experimenter (e.g. to sort, to wait; Zelazo, Carter, Reznick, & Frye, 1997). Using multiple measures with varying levels of difficulty across a range of contexts, and a combined data- and theory-driven approach to study how EF is profiled in the sample, meant that performance could be more ecologically valid, and that group differences could be dissociated in terms of EF underlying constructs.

A clear limitation of the current study is the small sample size relative to the desirable value for EFA/CFA methods. Post hoc power calculations using chi-squared difference testing (a common approach in SEM) indicated a modest power of 44% to detect the touchscreen group effects on CF and IC EF factor scores (Model 1b). This means that the EF constructs found might not generalise to the general population, or even be stable across this sample. Furthermore, the sample size in the current study precluded a detailed approach using multiple SEM models to test longitudinal associations or associations with attention measures. Although the current sample is small for SEM, and thus the current findings need to be interpreted with caution, the descriptive statistics and the group comparisons (uncorrected for multiple comparisons) for the observed outcome measures tend to support the results from the CFA. For the WM EF lab-tasks (Delayed Alternation and Spin the pots) the high users had a consistent reduced mean score, and the difference between the groups for the DCCS (CF measure) was marginally significant. The same tendency is seen in the cool-IC measures: in the Go/No-go Task the proportion of successful inhibiters is 88% in the LUs group, compared with 68% in the HUs group; and proportion of successful anti-saccade behaviour was marginally significantly different between groups at 3.5 years. This pattern was also evident in the parent-report measure of inhibitory control (which was significantly different between the groups). Only the delay of gratification tasks (Snack Delay and Glitter Wand) do not show a pattern of poorer performance on EF in the high users group.

In this chapter, I have applied a combined data- and theory-driven approach to investigate EF performance among children with high and low touchscreen users. This study contributes to the literature by presenting preliminary evidence that, as a group, high users show worse EF performance particularly on measures related to cognitive flexibility (including maintaining and updating, which are both related to working memory, and shifting). To further our understanding of why high users might fail to switch or to maintain a strong goal and task set representation, it is important that future studies investigate the associations of EF performance with abilities related to attention control, and dissociate between different types and contexts of use.

5.5. Summary of Chapter 5

- This chapter investigated whether group-level differences in executive functions (specifically working memory, WM, cognitive flexibility, CF, and inhibitory control, IC) occurred between children who have different levels of touchscreen use.
- This chapter also reported on how multiple measures of EF were associated at 3.5 years.
- Results using an Exploratory Factor Analysis and Confirmatory Factor analysis found that WM and CF observed measures could be measured by a single latent factor (which I named Cognitive Flexibility) supporting the idea that these constructs overlap considerably still in pre-school age (as it has been shown in toddlerhood).
- Results also showed that IC measures were better dissociated into two separate factors (which I named Inhibitory Control and Delayed Gratification), supporting the idea that IC is not a unitary construct at this age.
- In terms of touchscreen media use, the results showed that high users had reduced cognitive flexibility (both WM and CF).
- Inhibition also seemed to be related to touchscreen use, but the effect was confounded by family media environmental factors (i.e. it was no longer significant when co-varying for background TV in the home).
- Inhibition, as measured by delay of gratification tasks, was not significantly related to touchscreen use.

Chapter 6:
General Discussion

6.

6.1. Introduction to final chapter

The overarching goal of this PhD work was to longitudinally investigate the development of visual attention and executive function in infants, toddlers, and pre-school children who differed broadly in terms of their experience with mobile touchscreen devices (i.e. tablets and smartphones). To do this, I used a longitudinal cohort, part of the TABLET project (see Chapter 2), and a combination of developmentally appropriate neuroscientific methods, including eye-tracking based gaze-contingent tasks, and behavioural ones. In the previous chapters I have 1) provided the general literature background for this thesis, reviewing theoretical models investigating visual attention and EF, discussing past research on digital media effects (mainly television and videogames), and describing the main pathways proposed for such effects; 2) introduced the main methodology used in this thesis (i.e. the longitudinal dataset from the TABLET project), described the specific details and limitations of a quasi-experimental design of naturalistic behaviour, and outlined the analytical techniques applied within this thesis; 3) described the three empirical studies (Chapter 3 to 5) carried out within this thesis to fulfill the initial aims that were set.

Revisiting initial aims of this thesis

The initial specific aims of this thesis were twofold. The first aim was to investigate the development of visual attention, in terms of detailed cognitive assessments of bottom-up and top-down attention control, in relation to the use of touchscreen devices (indexed by parent-report). This aim was addressed in Chapter 3 and 4 of this thesis by dissociating the aforementioned components of attention and also testing the interplay between the two (i.e. situations where saliency-driven processing competes with selection based on internal goals). The second aim was to investigate EF performance in pre-school children in relation to their levels of use of touchscreens, following the view of EF that puts its putative constructs (updating, inhibition, and shifting) as later cascading products of typical development of attention control. This aim was addressed in Chapter 5.

In the present chapter, I summarise the findings of these empirical studies and critically discuss them from a broader perspective, highlighting how findings from the different chapters can be connected, and discussing potential implications for developmental science. I then examine the limitations of this work and finally propose future directions for studies to follow-up on the work described in this thesis.

6.2. Summary of findings

In Chapter 3 I investigated visual attention using gaze-contingent eye-tracking which showed, for the first time, that toddlers and pre-school children with high touchscreen use were faster at saliency-driven attention (indexed by the latency to find a target on the single search condition of a gaze-contingent Visual Search Task), and that concurrent amount of use, but not earlier use, was linearly associated with this saliency bias. No differences between user groups were found for trials requiring goal-driven attention control (indexed by the latency on the conjunction search condition of the same task). Then, in Chapter 4, I followed up on these findings and investigated whether the previously found attention pattern would generalize to tasks where a conflict between saliency- and goal-driven responses were present. I again used contingent eye-tracking to test performance of high and low touchscreen users on infant saccadic control tasks. Results from Chapter 4 suggest that extensive exposure to touchscreen devices was, again, associated with a quickening of attention to peripheral salient onsets (indexed by the latency to look to a peripheral stimulus on the Baseline condition of the Gap-Overlap Task and a distractor cue on the Anti-saccade Task). This faster orienting was concomitant with reduced performance in measures of top-down attention control (indexed by the disengagement effect of the Gap-Overlap Task and the proportion of anti-saccades on the Anti-saccade Task). In Chapter 5 I investigated if a reduced executive performance extended to EF tasks (both screen based and real world tasks) by testing differences between high and low touchscreen media users at 3.5 years. The results of Chapter 5 suggest that high users have reduced cognitive flexibility (indexed by an EF factor that includes both updating and shifting tasks). Inhibition too seemed to be related to touchscreen use but the effect was confounded by family media environmental factors (i.e. it was no longer significant when co-varying for background TV in the home). Further, inhibition, as measured by delay of gratification tasks, was not significantly related to touchscreen use.

6.3. Implications of results

6.3.1. Saliency bias

The collective results from Chapter 3 and 4 show, for the first time, that young children who are high users of touchscreens orient to salient targets in a visual scene faster than low users across different tasks aimed to measure visual attention. This pattern was evident in contexts where saliency was predictive of task-relevancy (i.e. in Visual Search, the "popping-out" red apple was the search target), and also in contexts where saliency acted as a distractor and could delay the appearance of more relevant and interesting stimuli (i.e. in the Anti-saccade task, a saccade to the "flashy" distractor delayed a look to the target site where a reward would immediately appear). Furthermore, there was no evidence of faster orienting when endogenous processes were required (i.e. in serial visual search, in the overlap condition of the Gap-Overlap Task, and when doing an anti-saccade).

These are novel findings that, as far as I know, have not been reported before in the context of digital media use. Several studies in the video gaming literature have shown general faster processing speed in action video games experts (e.g. Dye, Green, & Bavelier, 2009a). However, in the findings reported within this thesis, the effect is seen specifically in conditions, or to stimuli, that trigger exogenous attention, rather than a generalized speed of processing. In the television literature, one study has shown frequent online triggering of reflexive automatic responses during fast-paced movie clips (Lillard, Li, & Boguszewski, 2015b), but no study has reported systematic differences in exogenous processing dependent on children's media habits or level of regular viewing of such fast-paced entertainment media. This could be because, in general, researchers in the digital media field have not used detailed neurocognitive methods that allowed them to observe this effect (Kostyrka-Allchorne, Cooper, & Simpson, 2017a); or because there is something specific about touchscreen media platforms that confers this effect to users.

Indeed, the studies within this thesis differ substantially from other studies tackling a similar research question during early childhood, by employing rigorous neuroscientific methods to investigate visual attention dynamics, rather than using parent-report (Christakis et al., 2004) or observational measures of attention (i.e. during child play; Kostyrka-Allchorne, Cooper, Gossmann, Barber, & Simpson, 2017c), that are usually more dependent on higher-level processes such as effortful control and self-regulation. Eye-tracking is a relatively innovative method in the field, very rarely used in naturalistic studies of television viewing habits, but one that allows the study of the low-level attention dynamics and the visual sampling process with a fine-grained temporal resolution (T. J. Smith & Saez De Urabain, 2017). Eye movements enable the selection of specific information at any point in time and shape the visual experience (Findlay & Gilchrist, 2003). Early in life, they are in a way part of an adaptive evolutionary strategy to achieve an optimal performance in the environment one is born in, by shaping our attention bias and supporting perceptual narrowing (Frank et al., 2009; 2012; Kwon et al., 2016; Werchan et al., 2019). In an unconstrained visual space, the development of this sampling or selection process is thought to be largely genetic (Fan et al., 2001; Kennedy et al., 2017). However, in a screen scenario, eye movements are largely attributed to very specific features of the scene and systematically guided to very rigid regularities (Mital et al., 2010; T. J. Smith, 2012; van Renswoude, van den Berg, Raijmakers, & Visser, 2019; Wass & Smith, 2015). High users of touchscreens may develop their attention bias to saliency partially based on these regularities; leading to faster selection and orienting particularly to salient features. However, it is still unclear if high users also display this saliency bias in the "real-world", i.e. when looking at scenes that are not on a screen, or whether this pattern is just displayed when looking at a scene on a screen.

This effect (saliency bias) seems largely specific to touchscreen use, rather than being dependent on family television viewing habits, as suggested by the lack of an effect of the covariate (Background TV) on follow-up analysis. This specificity to touchscreen devices might be driven by the interactivity afforded by the platform, which allows the user to learn specific local associative connections given the stronger pairings between events and motor responses provided (D. R. Anderson & Davidson, 2019). Moreover, the results presented suggest that this saliency bias and selection-history effect is specific to concurrent touchscreen use, rather than an effect that persists even if children stop using the devices and change their media habits. This suggests this bias is dependent on a very dynamic and plastic system, and argues against an hypothesis that these results are driven by pre-existing temperament differences (or other traits related to attention control) between user groups. It is still unclear if this bias is seen in older children and adults, although comparable reports of dynamic history-driven selection in adults have been shown in recent years (B. A. Anderson et al., 2011; Theeuwes, 2019).

Another question emerging from this finding is whether the faster bottom-up attention in high users is a potential indication of relative different levels of activation of the alerting attention system in high users. High phasic alerting and higher levels of arousal that can induce faster shifts of attention and the activation of response codes that lead to faster (oculo)motor responses (de Barbaro, Chiba, & Deák, 2011). Selective attention is generally affected by arousal throughout the lifespan (Aston-Jones & Cohen, 2005; Kleberg, del Bianco, & Falck-Ytter, 2018; Mather, Clewett, Sakaki, & Harley, 2016), and increases in phasic alerting are related to enhanced attention to novel and salient stimuli (de Barbaro, Clackson, & Wass, 2017; Kleberg et al., 2018), either relevant and irrelevant ones (Weinbach & Henik, 2014). Additionally, phasic alerting has been shown to increase visual search speed in adults (Asutay & Västfjäll, 2017), and to speed visual orienting to pop-out targets in infancy (Kleberg et al., 2018). It is plausible that the saliency bias found in high users of touchscreens is thus a marker of a relatively higher alerting system, but this hypothesis cannot be addressed with the studies presented.

6.3.2. Top-down difficulties

The results from Chapter 4 and 5 suggest, overall, that high users of touchscreens have difficulties with cognitive control, particularly with overcoming their saliency bias in order to achieve the task goal (i.e. inhibiting a pro-saccade to a salient cue to receive a reward faster in the Anti-saccade Task), and in situations that require them to update and shift between task sets' abstract representations (i.e. in the Dimensional Change Card Sorting Test, in the Spin the Pots Task, and in the Delayed Alternation Task). I have argued that high touchscreen users might develop more rigid latent representations on a task which leads to less flexible behaviour and a weaker representation of abstract sets/goals (Kharitonova, Chien, Colunga, & Munakata, 2009) – see Chapter 5.

These findings can be interpreted as impaired development of executive attention. Both disengagement of attention and the ability to anti-saccade are measures more likely related to the executive network (Conejero & Rueda, 2017; Hendry et al., 2016). The attention executive network greatly overlaps and shares substrates and primary neurotransmitters with functions related to cognitive control, i.e. maintenance and switching of mental sets (Posner et al., 2012). It could be that the evidence presented in these two chapters point to an underdevelopment of the executive attention network, which could arise from the displacement of opportunities for "training" of this network and for EF scaffolding from the environment (i.e. parents) when using mobile digital media. Another explanation could be that a similar pathway of influence could lead both to the saliency bias discussed above and the cognitive control failures discussed here: the constant triggering of oculomotor (and motor) responses to perceptual salient features (that leads to a saliency bias) might cause a latent representation of task sets and goals to be stronger for high users. Perceptual saliency has been shown before to make cognitive flexibility more difficult (Doebel & Zelazo, 2015) so this might make it challenging for high users to shift to a new representation, and/or make high users prioritize latent representations over abstract conceptual relationships (D. R. Anderson & Davidson, 2019). Still, this does not imply that the two phenomena, bias towards saliency and stronger latent representations, are necessarily related. This does not seem to be the case according to preliminary results on the cross-sectional associations between saliency bias (i.e. single visual search latency) and cognitive flexibility in this dataset (i.e. DCCS score; see Appendix 5b).

An alternative view to the one just presented might posit that these findings do not point necessarily to the disruption of top-down attention control or an under-developed EF system, but instead to an adaptive strategy of behaviour. It may be that high use of touchscreen media does create a "bias" towards salient sensory input, which leads high users to select exogenous/external objects faster and more often than low users. This rapid activation of motor response codes in the presence of exogenous visual targets has been previously related to the notion that video games experts possess greater control over executive function and response, an idea that is consistent with past studies observations (Castel et al., 2005; Dye, Green, & Bavelier, 2009b; Green & Bavelier, 2003; West et al., 2013). Put another way, given that this pattern of attention selection might be based on high users' experience and observed statistical regularities in the current task context, this process could be regarded as a process of adaptation to the environment in which a child is raised (Johnson, 2011). When children spend time with interactive media, they are immersed in a virtual world instead of the real world. It is unclear yet how this affects children's understanding of the real world. In the previous chapters I argued that, possibly, the use of touchscreen devices allows children to make stronger pairings between physically contingent stimuli-response-goals (latent representations) but rely weakly upon abstract representations of internal goals. Learning statistical regularities is an important human adaptive function, and could potentially benefit learning in the virtual world and in a multimedia information-oriented society.

However, children also need to engage in the "real-world". From the studies presented in the previous chapter, an hypothesis arises that a stronger reliance on sensory input could lead to poorer executive control, with high users performing lowest in lab-based EF (including executive attention measures), and also in parent-report of everyday functioning of EF (i.e. inhibitory control in the CBQ).

Enhanced visual search (Kaldy et al., 2011), slower disengagement of attention (Elsabbagh et al., 2013), and EF difficulties in cognitive flexibility (Mackinlay, Charman, & Karmiloff-Smith, 2006), are markers that have been seen related to Autism Spectrum

Disorders (ASD). The "real-world" is complex, uncertain (i.e. full of irregularities), and dynamic. While our brain works in a constant flow of predictive coding (generating predictions about the very near future events) and error-correction (updating one's predictive model based on comparisons of the predicted and observed sensory input, i.e. learning), children learn to cope with a certain degree of imprecision in their predictions in the face of unpredictable or noisy circumstances, by updating the weight or reliability estimates to prediction errors in a context-sensitive manner (Clark, 2013). With this regard, prediction errors can be seen as bottom-up processes (sensory sampling to compare to model), whereas predictions are seen as top-down processes. The complex interplay of these processes is crucial to detect changes in the environment and induce new learning; and to be able to generalize inferences in situations where exact matches (irregularities) are not present.

Some have argued that an atypical updating of weightings to prediction errors (i.e. bottom-up) is a primary dysfunction in ASD (Van de Cruys et al., 2014), in a way that individuals with ASD put a higher and more fixed weight on their low-level sensory processing (prediction errors) independently (i.e. inflexibly) of context (Palmer, Paton, Hohwy, & Enticott, 2013; Pellicano & Burr, 2012). In this manner, ASD individuals benefit from very regular situations and exact associations, but fail in inferring generalizations in more irregular contexts (i.e. form abstract representations), such as natural or social situations, and in sampling (i.e. guide attention) based on top-down relevancy (since bottom-up stimuli is seen as always relevant).

To be very clear, my point here is not to draw a comparison between high touchscreen users and children with ASD, neither it is to suggest that touchscreen use leads to ASD symptoms. But the framework presented might be useful to understand the findings presented in this thesis. The world inside a touchscreen is incredibly regular compared with the natural world. Perhaps by being more often presented with this regularity, high users of touchscreens give relatively more weight on their bottom-up processes and prediction errors, which confers an advantage in fixed contingency learning on the screen-based tasks (the case of visual search), accompanied by an over-selectivity in attention in situations where multiple cues compete (the case of the Anti-saccade and the overlap condition), and a difficulty in adaptive control (i.e. EF) – the same pattern of behaviour reported in ASD. One important difference in high users, relative to ASD children, is that their overweighting of bottom-up processes (i.e. the saliency bias effect) seems to be short-term and change accordingly to concurrent usage, suggesting that can easily be updated; whereas in ASD the over-reliance on predictive errors is seen as a chronic and primary dysfunction (Van de Cruys et al., 2014).

6.4. Revisiting pathways of influence in light of this thesis results

There are important considerations to take from the results within this thesis if one looks at the pathways of influence previously proposed for the digital media effects on the developing mind. First, although not previously reported in the literature concerning television, the saliency bias I repeatedly found in high users of touchscreen devices seems to give partial support to theories that come from this literature that state that digital media content *triggers reflexive orienting responses* and in that way strengthens bottom-up attention networks (Christakis, 2009; Lillard & Peterson, 2011; Zimmerman & Christakis, 2007). Results also seem to give partial support to the view that digital media displaces top-down internal control processes (Christakis et al., 2004; Singer, 1980; Zimmerman & Christakis, 2007). It is not clearly specified in this literature how these two processes would be connected, but I propose that a fast and weighted bottom-up network (conferred by touchscreen use), which works well in detecting environment regularities and establish associative learning (D. R. Anderson & Davidson, 2019), might hinder establishment of more abstract generalizations and representations (necessary for cognitive control in the always changing and uncertain "real-world").

Another account for the results presented, particularly the reported findings of faster saliency-driven attention, concerns the *stress-inducing/ overstimulation hypothesis*. Higher levels of arousal (which are associated with more reactive states; de Barbaro et al., 2011) are related to the alerting network of attention, in a way that an alerted state (high arousal) acts adaptively by prioritizing the processing of behaviourally relevant, bottom-up, visual information (see above), but is detrimental when selective attention to less salient details is required (Weinbach & Henik, 2014), and when several responses compete (Callejas, Lupiáñez, Funes, & Tudela, 2005; Weinbach & Henik, 2014). It is thus a plausible hypothesis, but not currently tested in this thesis, that high users display faster gaze shifts to salient quick peripheral stimuli driven by higher arousal levels, while not benefiting from these arousal levels in more demanding scenarios (i.e. conjunction search or scenes with competing stimuli). It would be interesting to follow-up on this hypothesis and evaluate if high users present more exploratory attention patterns related to the alerting network (e.g. more gaze shifts) and higher arousal levels (e.g. assessed through pupil dilation or heart rate) than low users, in complex screen-based and "real-world" scenes.

Importantly, while I have shown that high users have an altered attentional control profile, it is unclear whether the effects found are due to an individual behavioural difference between users that is presented across contexts (i.e. high users have a general faster bottom-up attention and/or higher baseline arousal levels) or if they are due to a state that is induced by the familiarity with the screen in some users and not others (i.e. high users' familiarity with the screen induce higher arousal levels and/or shift visual processing to bottom-up). Put another way, it can be that touchscreen use leads to a general shift of arousal levels in these children (as it was proposed by other researchers, e.g. Huizinga et al., 2013) so they have generally higher levels of arousal and thus are more distractible; or it can be that the screen context is more meaningful to high users (similarly to socially relevant cues in alerting-induced responses; Kleberg et al., 2018) and so it induces greatest alerting and faster bottom-up processing. Dissociating the two is an extremely important avenue for future research, but also it would be important to understand the long-term consequences of these behaviours.

Another important piece that might be interesting to examine concerns the hypothesis that digital media *disrupts rewarding pathways and networks*. Because interactive media triggers multiple stimulus-response-goal associations, it activates the reward systems and the release of dopamine in anticipation of reward (D. R. Anderson & Davidson, 2019). The media is then perceived as more rewarding and engaging. However, it is unclear whether the development of rewarding systems is disrupted by this systematic process. ADHD patients, who show altered rewarding processing (Tripp & Wickens, 2009), have shown similar evidence of a bias towards dynamic visual saliency features whilst free-viewing TV (Tseng et al., 2012), and have shown reduced suppression of the automatic pro-saccades in the Anti-saccade Task (Munoz et al., 2003; Munoz & Everling, 2004). However, the results presented within this thesis cannot establish whether salient features are intrinsically more rewarding to high users or whether high users have altered reward processing.

6.5. Limitations of this research

6.5.1. The specificity of touchscreen media effects

The results presented in this thesis, particularly the enhancement in saliency-driven attention from concurrent touchscreen use, seem largely independent of other known factors such as television exposure, highlighting the potentially unique role of these devices for the developing mind. However, it is important to acknowledge this thesis' limitations in the assessment of the media environment and the absence of measurement of other potential variables that could explain the effects found. In the studies presented, the parent-report measure of household Background TV was used as a covariate in analysis, as an index of the family/household media environment that could index the child's television viewing. However, this measure is not a direct assessment of either the television the child watched or the child-directed programming the child was exposed to. Thus, the possibility that the saliency bias effect can be conferred by any medium that provides infant and child-directed content (that rely on perceptually salient features) cannot be discounted. Against this hypothesis, it is reassuring that Background TV in the current sample correlates fairly well with measures of child-directed content drawn from media diaries filled prior to the visits [positive ($r > 0.45$) significant correlation in all visits, see Chapter 2]. Further, faster bottom-up processing has not been reported in previous literature concerning television effects, which supports the view that this saliency bias is specific to touchscreen media use (which relies on perceptually salient features and includes a component of interactivity and contingency that strengthens oculomotor bottom-up responses). Still, an alternative hypothesis is that this effect has not been investigated exhaustively by television researchers as, usually, researchers have looked to endogenous/ executive measures, typically through parent-report questionnaires of attention difficulties (Kostyrka-Allchorne, Cooper, & Simpson, 2017a; Nikkelen et al., 2014).

Furthermore, I acknowledge that a key limitation and criticism of this work is the potential for biased parent-report of screen time. Unfortunately, objective tracking methods such as passive sensing apps (e.g. screenomics[14]) embedded in the multiple devices a child uses (e.g. own tablet, parent's smartphone), which have been used in adult samples (e.g. Lin et al., 2015; Reeves et al., 2019), could not accurately and unobtrusively capture a toddler's touchscreen exposure, given that they cannot reliably inform whether it is the toddler who is using the screen. To do this would require a child's point-of-view video camera (e.g. L. B. Smith et al., 2015), or a face-detection algorithm, that could influence parent willingness to participate.

However, an effort was made to draw indirect validations of the accuracy of parental self-report and support the study design. Firstly, the question deriving the user group measure at each visit, 'On a typical day, how long does your child spend using a touchscreen device (tablet, smartphone or touchscreen laptop)?', was an easy-to-understand question designed to maximise the validity of parent-report responses

[14] *http://screenomics.stanford.edu/*

(Morsbach & Prinz, 2006) by: 1) minimising strategies for estimation by asking for a specific duration rather than a percentage of time, which has been shown to improve reporting accuracy (Bless et al., 1996); 2) minimizing response bias through an open-ended question ("How long...") rather than a closed format one with specified time slots, which has been shown to cause greater response bias for television viewing (Schwarz, Hippler, Deutsch, & Strack, 1985); 3) by reducing socially desirable responding through a technology-administered, online questionnaire approach, rather than in-person or paper-based responses, which increases the reporting honesty (Morsbach & Prinz, 2006).

Secondly, the analytic strategy, because it relies on broadly defined levels of touchscreen use (i.e. groups based on median split) and not the actual amount of touchscreen time, mitigates potential issues about the precision of parent-reported time. Moreover, one would still expect the variation in parent-report to be positively correlated with their child's actual screen time (as shown in prior studies; D. R. Anderson et al., 1985; Lin et al., 2015), which supports the use of touchscreen time levels (relatively to the median) as the key variable in the design.

Thirdly, the variation across children in parent-report touchscreen-time was validated against the duration of touchscreen activities in the parent-report media diaries, which showed moderate associations throughout visits (significant positive correlations ranged from $r = 0.49$ to $r = 0.63$, see Chapter 2).

6.5.2. The problem of causality and direction of effects

The studies presented in this thesis are based on naturalistic observation and correlational data. As such, the associations found between media use and outcome behaviours might be confounded by children's pre-existing behavioural traits or family environmental factors. Even when recruitment samples are matched and a rigorous longitudinal design is applied, as it is the case of this thesis studies; the lack, for example, of measures of EF abilities across time, leaves the question open of whether EF protective factors early in life might have hindered any effects of touchscreen use later on development. EF skills are seen as a protective factor to other risk factors, for example in the context of developmental disorders, in a way that better EF tends to lead to more resilient and compensatory capacities (Johnson, 2012). Reliably measuring EF in infancy and toddlerhood is a matter of contemporary investigations (Fiske & Holmboe, 2019; Hendry et al., 2016). For that reason, in this thesis, EF was measured indirectly at early time points through attentional precursors.

One would have to look at multiple measures across multiple time points in large samples (so that cross-lagged models in a SEM framework could be applied) to fully understand the direction of the effects presented. Yet there are two important points about this thesis studies that tentatively support the view of technology as a factor of environmental influence. Firstly, I have shown that parent-reported child temperament measures (IBQ/ ECBQ), that are known for tapping into executive attention and EF (e.g. effortful control), do not differ at 12 months between groups (see Chapter 2). This suggests that, at the age of recruitment, high and low users of touchscreens had similar executive control capacities. Secondly, the main findings reported within this thesis are concurrent associations, based on group memberships that changed over the years. If a susceptibility to be a high or low user of touchscreen media arises from genetic traits related to perceptual coding or executive performance, it would be logical to think that the same children would be having similar habits, and performance, across time. Further, it would not be expected that by changing between touchscreen use groups, the individual's group would also be changing performance.

The main aim of this thesis was to test if there was a link between touchscreen use and attention and EF profiles, but a foreseen limitation of this project was always the impossibility of demonstrating causality with such observational studies. The studies presented are in no way a demonstration of a causal influence of touchscreen media use (but see below how they can inform future studies addressing causality) and this is a point that needs to be emphasized when considering implications for science dissemination.

6.5.3. Sample size

Sample size is inevitably a consideration all research needs to address. As discussed in Chapter 1 and 2, the project that this thesis is based on was exploratory in nature given the relatively recent introduction of tablets and smartphones in the family environment, and the consequent small amount of evidence linking its use with attention and EF, in comparison to the literature drawn from other conventional media. There are three particular limitations associated with these studies (modest) sample size. Firstly, the current sample is a relatively low-risk sample (i.e. high maternal education and no atypicalities in development) which might lessen more negative (e.g. low SES families might not have access to paid curated educational content) or positive (e.g. parents of children with neurodevelopmental disorders might benefit from content developed specifically for their children) effects of screen time.

Secondly, the modest sample size limited the statistical approaches that could be applied to answer the questions within this thesis. In particular, in Chapter 5, multiple measures of EF were used to study in detail the performance of high and low users. To better understand how EF was organized and related to touchscreen use, and avoid multiple individual statistical tests to all those measures, I used a SEM framework. However, SEM is a very sensitive tool to sample size, and results are likely to be less robust with small samples. It is thus crucial to take these results as only preliminary evidence for the relationship between touchscreen media use and EF.

Another related important limitation of these studies' sample size is that it did not allow different profiles of use of touchscreens to be dissociated. Indeed, the approach taken assumed that touchscreen devices, given the interactive, mobile, and immersive nature of the platform, would affect attention and EF development independently of *where*, *when*, with *whom*, and *why*, that use happened. However, it seems likely that the content and context of technology use on a touchscreen produces a differential impact, as it has been shown in studies addressing conventional media exposure. For example, Barr and colleagues (2010) found that EF was associated with adult-directed television viewing, but not with child-directed program viewing. Nathanson and colleagues (2014) also found that the quality of the content was an important factor in the concurrent relationship with EF outcomes, with educational cartoon viewing being negatively associated with EF score, while educational and developmentally curated entertainment (from the Public Broadcasting Service) was positively associated with EF. The available evidence on touchscreen media use, from the TABLET project, already demonstrated differential effects on fine motor skills of active scrolling of the screen versus video watching on a touchscreen (Bedford et al., 2016). Thus, the effects presented in this thesis might not be generalized across all types of use and should be followed by future studies addressing the questions emerging from it with hypothesis-driven study designs.

6.6. Future directions

6.6.1. Attention as a mediator of the association between touchscreen media and Executive Function

Two main findings are drawn from the collective studies presented in this thesis: 1) selective attention in young high users of touchscreens is more bottom-up driven, and 2) executive performance in this group seems to be reduced. Although in Chapter 4 I showed that the reduced top-down control was driven by faster exogenous attention, it is still unclear how these processes are interconnected, and whether one is a consequence of the other. In addition, it is still unclear in the EF literature how attentional processes, namely executive attention, support or drive EF development in a predictive manner (Hendry et al., 2016). Based on the results within this thesis, I proposed a hypothesis that a fast and weighted bottom-up network (conferred by touchscreen use) would hinder the establishment of more abstract generalizations and representations (necessary for EF). Based on this hypothesis, bottom-up attention processes would mediate the association between touchscreen use and EF. Preliminary results from the current studies do not lend much support to this model, given that exogenous attention (single search latency) at 18 months and at 3.5 years does not seem to be related to EF at 3.5 (Appendix 5b), but this should be properly tested in future studies. To directly test this model, one would need to run a pathway analysis (in a SEM framework) with a large sample size and measures of touchscreen media use, attention, and EF across different time points.

6.6.2. Bottom-up attention in the "real-world"

To understand the associations of early life touchscreen media use and cognitive development, particularly attention and executive control, I have conducted the experimental behavioural studies within this thesis and consistently showed that high-users have faster exogenously-driven attention (i.e. faster pop-out search and faster attention orienting to salient peripheral cues). However, it is still unclear whether this attentional behaviour (which proved to be efficient on the screen-based tasks) is a high users' trait (i.e. the behaviour will be applicable across a wide range of contexts) or a state that is induced in the presence of a digital screen and applied only in this context. It is crucial to address this question and investigate whether high users' gaze behaviour is more saliency-driven in a "real-world" context, for example, while doing a 3D puzzle (rather than one on a screen), while different salient items are presented around the visual field. This could be implemented with novel eye-tracking methodologies (e.g. head-mounted eye-tracking) that allow monitoring of gaze behaviour (to study selective attention) and pupil dilation or wearable heart rate monitors (to study arousal dynamics correlated with an alerting state) in naturalistic settings.

6.6.3. Neural correlates of executive performance

High users of touchscreens in the results presented seem to be more bottom-up driven, at least in the context of a screen-based task. I also showed that high users faster bottom-up attention compromised their performance in endogenous measures of attention and that touchscreen use was also associated with reduced cognitive control off-screen. However, it is not clear how the interplay between these two processes works, and specifically if the reinforcement of bottom-up networks can potentially inhibit the engagement of top-down brain networks. To study activation and inhibition of brain processes one would need to look at the neural correlates of executive control. The prefrontal cortex has been suggested as having an important role in guiding behaviour and cognitive control, including cognitive shifting and inhibition throughout development (Diamond, 2002). Recent neuroimaging research has supported this idea showing that the lateral prefrontal cortex is significantly activated during executive performance in toddlerhood and pre-school years, including cognitive flexibility (Moriguchi & Hiraki, 2009) and inhibitory control (Moriguchi, Shinohara, & Yanaoka, 2018). Neuroimaging methods are often more sensitive to changes in child development than behavioural measures are, and hence of particular importance when studying environmental influences on brain development.

To understand the role of touchscreen use in attention and executive function development, particularly to confirm reduced top-down attention guidance from habitual touchscreen use, it would be interesting to directly test toddlers' behavioural and neurophysiological responses, for example testing children's brain lateral prefrontal cortex activation using fNIRS while performing executive control tasks, on-screen (e.g. Anti-saccade) and off-screen (e.g. the DCCS).

6.6.4. Bi-directional media effects

A key question emerging from the findings reported in this thesis, and generally in the field, concerns the causality and direction of media effects, i.e. is the media use the result of underlying traits and/or is it a causal factor in the development of these traits. Follow-up studies must focus on exploring the associations between toddler digital touchscreen media use and pre-school executive performance, by testing bi-directional associations between measures. Two hypotheses can explain the cross-sectional and longitudinal findings reported in this thesis. It could be that, early in development, intense media use leads to attention control problems and subsequent EF difficulties (e.g. through displacement of opportunities to develop voluntary control of attention or habitual reliance on bottom-up attention processes); or it could be that early life emerging constructs of EF-related difficulties (i.e. attention and executive control) might lead to more media use (e.g. if parents use media as a tool to regulate their children's difficult behaviour or if these characteristics are promoting the pursuit and engagement of digital media) and subsequent EF difficulties (driven by these pre-existing traits rather than the media use). No studies to date have examined these longitudinal reciprocal associations with EF in infancy and toddlerhood. To answer this question it would be necessary to use a cross-lagged SEM approach that would require extensive large scale follow-up studies, and assessment of EF at multiple points in development, not feasible within the scope of this PhD.

6.6.5. Randomized control trials

Cross-lagged structural equation modelling of media use and cognitive outcomes, assessed through multiple time points, allow directionality of associations to be teased apart and further our understanding of the mechanisms and pathways involved. However, any study that is based on observational and correlational associations is insufficient to demonstrate the causality of effects, because of single or multiple unobserved confounding variables that may explain the apparent correlation at different time points. To provide a causal evidence-base for the impact of touchscreen time on toddler attention control and EF, one would have to carry a randomized controlled trial, that allocates families randomly to different experimental intervention arms, e.g. one arm where families are instructed to avoid any type of screen time, and one arm where families are recommended to use digital screen media. Such a project is very problematic, ethically, to be run given that the current guidelines for younger children advocate avoidance of screen media before the age of 18 months (AAP Council on Communications and Media, 2016). Furthermore, research designs also need to ensure participants' adherence to both intervention arms and come up with control conditions (i.e. alternative activities to screen time) that do not produce a positive effect (otherwise effects cannot be attributed to the lack of screen time *per se*). More mindful experimental designs, that focus on specific screen time guidance (e.g. the hour before bed) and include parental guidance and educational material parallel to the screen intervention, might work well to overcome these issues and establish causal evidence in the field.

6.6.6. Online processing of digital screen and touchscreen content

In this thesis, I set up an investigation of the impact of (undifferentiated) use of touchscreen devices on children's attention and EF, with the underlying assumption that any activity on a touchscreen, even if watching a movie, would have a fundamentally different effect in the cognitive system compared to the same activity on a conventional media platform, like a TV set. It seems that touchscreen devices are, as a whole, triggering saliency driven attention, in a way that does not seem to have been reported before. However, future studies should elaborate the dynamics of attention (bottom-up and top-down), and the neural correlates of executive processing, dissociating different types of touchscreen media use (e.g. passive video viewing, interactive video-viewing). These studies should also test how the embodied experience conferred by these activities on a touchscreen (e.g. amount of motor control it requires, sense of agency it provides) is related to these attention patterns of online processing of content, given that the interactivity and physical contingency of the platform might play a role in establishing stimuli-response pairings (D. R. Anderson & Davidson, 2019).

6.7. Conclusion

This PhD thesis has presented a set of studies investigating visual attention and executive function among infants, toddlers, and children that differed in terms of their level of habitual use of touchscreen devices (i.e. tablets and smartphones). I have been able to repeatedly identify a bias in high-touchscreen-using toddlers towards salient features in a variety of gaze-contingent (eye-tracking based) visual tasks. This is the first time such a bias has been documented. This attention behaviour impairs high users' ability to control their attention in an internally-driven way. The real-world implications for this bias in environments that require executive function (including attention control) are also revealed in the last empirical chapter of this thesis, where findings point to difficulties in cognitive control in the same high-touchscreen-using children. These difficulties might arise because weighted perceptual bottom-up processes displace opportunities for scaffolding of executive processes, and/or because it hinders the representation and generalization of abstract goals and task sets.

The strengths and novelty of this research include the use of detailed developmental cognitive neuroscience methods to study attention (eye-tracking based), and the use of multiple complementary methods to study emergent EF functions, to tackle a pressing question with societal and educational implications. Further, the use of a longitudinal design and a well-characterised sample enabled the investigation of associations across time, which allow findings to be inferred more robustly.

Implications for future studies are varied. Firstly, future studies should replicate the saliency bias and reduced top-down control reported in these studies in "real-world" settings while applying neuroscientific methods to study the neural and physiological correlates of attention. Only this way, one can answer the question of whether the attentional pattern found in high users of touchscreens is a trait or a state induced by the presence of a digital screen. Secondly, investigating bidirectional dynamic effects and demonstrating causality are pressing action points in the media use and cognitive development field in general, so randomized control trials and large-scale studies with multiple data points are critical. Thirdly, going forward from this project, the content and context of touchscreen use need to be dissociated to better understand which particular features of a touchscreen are important for learning (and which type of learning it fosters) and thus can serve educational purposes, and which ones require some discussion by media developers and educators.

The work within this thesis has the potential (provided extensive follow-up studies) for great public impact of developmental science given that covers a topic of immense societal importance. Given the rapid rise in screen exposure in infancy and pre-school children and the current absence of rigorous scientific evidence to support the recommendations made by national and international agencies, I hope that the studies presented will garner scientific and public interest and collectively empower families and educators to make an informed decision around the topic.

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Appendix

2. *Chapter 2 Appendix*

RESPONSE SHEET

For TV/DVD: **A** = adult-directed programmes; **C** = child-directed programmes
For Touchscreen (tablet, phone or computer): **P**=passively watch videos; **A**= actively control videos (e.g, choose or scroll forward); **C**= call someone; **G** = play games; **E**= education apps; **D** = creative apps (e.g. drawing); **M** = listen to music
Rating scale: **1**=never, **2**=seldom, **3**=frequently, **4**=very frequently, **5**=DK (unknown or not applicable)

Date: 28/10/15 Day: Wednesday Normal day? Y	6am – 7am	7am-8am	8am-9am	9am-10am	10am-11am	11am-12pm	12pm-1pm	1pm-2pm	2pm-3pm	3pm-4pm	4pm-5pm	5pm-6pm	6pm-7pm	7pm-8pm	8pm-9pm	9pm-10pm	10pm-11pm	11pm-12am	12am-1am	1am-2am	2am-3am	3am-4am	4am-5am	5am-6am
TV/DVD																								
Touchscreen																								
Awake? (Y/N)	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N

Programme/ App name	**Device** (TV, DVD, tablet, phone, computer)	**Duration** (min)	Time spent focused on activity (%)	Child-initiated interaction (Rate 1-5)	Other-initiated interaction (Rate 1-5)	Another **adult** present (%)	Another **child** present (%)

Appendix Figure 1. Media time-diary example sheet.

3. *Chapter 3 Appendix*

3a. Alterations to procedure at the visit at 3.5 years

The procedure for Visual Search in the visit at the 3.5 years was altered when data collection was already ongoing. Twelve participants were presented with 26 continuous trials as per the procedure at 18 months; thirty-one were presented with 29 trials, 3 of them presented before instructions to find the red apple. When comparing within-participants single search reaction times (Single Search SRT) with task block (block pre-instructions, total of 3 single trials, and main block, total of 26 trials), including in the analysis the 31 participants who did the altered procedure, no differences between single SRT were found – see Appendix Table 1. When comparing between-participants with task procedure (children who were presented with 26-trials procedure with no instructions, and children who were presented with 29-trials procedure with instructions), including all participants who contributed with data for analysis, no differences between subjects was found on single search SRT – see Appendix Table 2.

Appendix Table 1. Within-subjects comparison on Single Search SRT, paired samples t-test.

Single Search SRT	N	Mean (SD)
Block pre-instructions	31	920 (475)
Block post-instructions	31	847 (331)
Within-subjects comparison	t(30) = 0.94, *p* = 0.355	

Appendix Table 2. Between-subjects comparison on Single Search SRT, independent samples t-test.

Single Search SRT	N	Mean (SD)
Group who did not receive instructions (Number of trials = 26)	12	964 (255)
Group who received instructions (Number of trials = 29)	31	877 (349)
Between-subjects comparison	t(41) = 0.78, *p* = 0.44	

3b. Processing steps for the Visual Search Task

Trial classification

Gaze buffer is pre-processed to exclude gaze offscreen, interpolate data and average eyes.

Online data extraction

1. Extract relevant variables from task files automatically exported at the end of the task administration: correct score, Search Reaction Time (SRT), skipped flag, type and set size.

Estimate quality metrics

2. Calculate the duration of the trial from the moment the array was presented to the event marker where gaze entered the target Area of Interest (or trial ended).
3. Calculate out of the entire trial length the proportion of missing gaze samples.
4. Check gaps of missing data and calculate the maximum value in milliseconds.

Overall trial validation

5. Trial validation is a logical AND of the following flags:
    a. Proportion no eyes < 25%.
    b. Maximum gap of missing data is < 500 ms.
    c. Time to find the target > 200 ms.

Trials that are false to any of these will be excluded from average scores.

Output variables

Output is written to an Excel file, with one row per subject * trial. Column headers are:

Variable	**Description**
ONLINE_CORRECT	Whether a gaze entered the target AOI (1 = target found before 4 secs, 0 = target not found)
ONLINE_SRT	Search time from trial onset to the moment target was found. Nan if ONLINE_CORRECT = 0.
ONLINE_SKIPPED	Flag: trial skipped by experimenter
TYPE	Type: SINGLE or CONJ
SIZE	Set size: 5, 9 or 13
DURATION	Trial total duration
PROP_NO_EYES	Proportion of missing data
MISS_MAX_GAP_VALID	Maximum gap of missing data

3c. Results of the pre-registered analysis

The 3.5 years longitudinal assessment visit was pre-registered on the Open Science Framework (Spies, 2013), where effects in search reaction times in the Visual Search Task at 3.5 years were planned[15] to be tested in a repeated-measures ANOVA with search type (single, conjunction) and size (5, 9) as within subject factors and usage group (high, low) as between subject factor. The results of this pre-registered analysis were very similar to the ones reported with the GEE, see Appendix Table 3. At 3.5 years, there was a main effect of search type on accuracy and search reaction time. There was no other main effects or interactions in the pre-registered repeated-measures ANOVA, but when

[15] *https://osf.io/xptua/*

we followed-up the findings at 18 months, by testing a main effect of usage group on the single search type reaction times, there was a main effect of user group.

Appendix Table 3. Summary statistics of the pre-registered repeated-measures ANOVA including search type (single, conjunction) and size (5, 9) as within subject factors, concurrent usage group (high, low) as between subject factor, and search reaction time as the dependent variable, in the Visual Search Task at 3.5 years. The sample included 18 LUs and 24 HUs.

	Visit at 3.5 years
Pre-registered repeated-measures ANOVA: Search Time	F (df_{IV}, df_{error}), p value
Search Type	**46.995 (1,40), p < 0.001**
Set Size	0.001 (1,40), p = 0.971
Group	2.822 (1,40), p = 0.101
Type*Group	2.237 (1,40), p = 0.143
Set size*Group	0.002 (1,40), p = 0.969
Type*Set size	0.278 (1,40), p = 0.601
Type*Set size*Group	1.841 (1,40), p = 0.182
Follow-up ANOVA in single search: Search Time	F (df_{IV}, df_{error}), p value
Set Size	0.264 (1,40), p = 0.610
Group	**5.857 (1,40), p = 0.020**
Group*Set Size	1.816 (1,40), p = 0.185

3d. Mean and Standard Deviation of Saccadic Reaction Time in the Visual Search Task

Appendix Table 4. Mean and Standard Deviation of Saccadic Reaction Time in milliseconds across search type and set size in the Visual Search Task, for each touchscreen use group, at 18 months and at 3.5 years..

Visit	**Type of search**	**Set Size**	**Usage group**	**Mean SRT**	**SD**
18 months	Single	5	LU	1362	437
			HU	1050	367
		9	LU	1143	410
			HU	1024	256
	Conjunction	5	LU	1307	518
			HU	1392	351
		9	LU	1569	426
			HU	1538	403
		13	LU	1644	653
			HU	1620	506
3.5 years	Single	5	LU	999	408
			HU	868	377
		9	LU	1059	458
			HU	736	296

Visit	Type of search	Set Size	Usage group	Mean SRT	SD
	Conjunction	5	LU	1393	530
			HU	1296	463
		9	LU	1344	392
			HU	1398	522
		13	LU	1657	337
			HU	1454	673

3e. Results covarying for Background TV

Follow-up models were run including Background TV as covariate. Only models where Background TV had a main effect are reported below.

A GEE model including user group (HU, LU), and set size (5, 9) as predictors of conjunction search SRT, including Background TV (min/day) as covariate, at 3.5 years (see Appendix Table 5 for full statistics) showed a main effect of Background TV, and in the same way to the results reported in Chapter 3, no significant set size, group, or interaction effect within conjunction search.

A GEE model including user group (HU, LU), and set size (5, 9, 13) as predictors of conjunction search SRT, including Background TV (min/day) as covariate, at 3.5 years (see Appendix Table 5 for full statistics) showed a main effect of Background TV, and similar result to the later model, only with a marginally significant effect of set size (which was significant in the model presented in Chapter 3).

Appendix Table 5. Summary statistics of GEE models including group, search type and set size as predictors of SRT in the Visual Search Task at 18 months, when adding background TV as a covariate. The final sample at 3.5 years included 18 LUs and 24 HUs.

Search Reaction Time GEEs	**3.5 years** Wald χ^2 (df), p value
Follow-up model restricted to conjunction search	
Set Size (5, 9)	0.356 (1), p = 0.551
Group	1.41 (1), p = 0.235
Background TV	**11.239 (1), p = 0.001**
Group*Set Size	0.164 (1), p = 0.686
Follow-up model restricted to conjunction with set size 13	
Set Size (5, 9, 13)	5.132 (2), p = 0.077
Group	2.141 (1), p = 0.143
Background TV	**7.417 (1), p = 0.006**
Group*Set Size	1.33 (2), p = 0.514

4. ***Chapter 4 Appendix***

4a. Group permutations and outcomes for recoding of the longitudinal stable group

For some children, touchscreen usage was not consistent throughout the study and they changed their group membership between visits. To recode touchscreen usage group so it could index children's touchscreen use across visits, the below scheme was used Appendix Table 6. To be considered for a stable usage group the child's group at infancy visits would need to match the usage group at the pre-school visit. If children missed visits, they were still included in a group if their usage was consistent on the other time points.

Appendix Table 6. Group permutations in the TABLET lab-sample and outcome longitudinal group classification, including number of children in each group.

INFANCY				PRE-SCHOOL	OUTCOME LONGITUDINAL GROUP	
12 mo		**18 mo**		**3.5 y**		N
LU	⇒	LU	⇒⇒	LU	**Low User**	12
HU	⇒	LU	⇒⇒	LU		2
HU	⇒	HU	⇒⇒	HU	**High User**	17
LU	⇒	HU	⇒⇒	HU		1
HU	⇒	LU	⇒⇒	HU		3
HU	⇒	HU		*Miss*		2
HU		*Miss*		*Miss*		3
LU	⇒	LU	⇒⇒	HU	**Unstable User**	6
HU	⇒	HU	⇒⇒	LU		5
LU	⇒	HU		*Miss*		1
LU		*Miss*		HU		1
					Total	53

4b. Processing steps for the Gap-Overlap Task

Offline trial classification

Gaze buffer is pre-processed to exclude gaze offscreen, interpolate data and average eyes.
Note that all Area of Interest (AOI) checking is done only on the x-axis. AOI is 2x the size of the original stimuli.

Sanity check (ensure this is a full trial, with uncorrupted data)

1. Check all relevant event markers are found.
2. Find where Peripheral Stimuli (PS) was presented: skip trials if PS was not presented in left or right side of the screen.
3. Find trial condition: 'GAP', 'OVERLAP' or 'BASELINE'.

Gaze to Central Stimuli (CS) – ensure that gaze was on CS at the start of the trial

4. Find contiguous sections of gaze within the CS AOI, from the period of CS onset to PS onset.
5. Find first contiguous section of gaze with length >24ms. Interpret this as orienting to the CS. Invalidate trial if no sections of gaze meet this criterion – *a*.
6. Find gaps in gaze data from CS onset to PS onset. Invalidate trial if any gaps of length >200ms are found – *a*.

Gaze to CS at PS onset – ensure that gaze was still on the CS at PS onset

7. Look for a gap in the gaze data within the CS AOI either side of the PS onset. Invalidate trial if gap is of length >100ms – *b*.

Gaze to PS

8. Find when gaze entered the PS AOI, from the onset of PS. This is the first sample of the first contiguous section of gaze within the PS AOI for at least 24ms (see step 4 and 5) – *c*.
9. Check for gaps of missing data of length > 100ms from PS onset to the moment gaze was found in PS AOI. Invalidate trial if any found – *d*.
10. Check that gaze has not entered the PS AOI for >50ms before PS onset – *e*.

Check gaze direction – ensure that gaze did not orient to opposite side

11. Define an AOI that mirrors the PS AOI (located on the opposite side of PS). Look for sections of contiguous gaze in this AOI from PS onset to the moment gaze was found in PS AOI. Invalidate trial if any gaps are of length >50ms – *f*.

Calculate SRT

12. Calculate Saccadic Reaction Time (SRT) as time from PS onset to first sample of gaze in PS AOI (see step 8).
13. Check bounds: 150ms < SRT > 1200ms. Invalidate trial if SRT out of bounds – *g*.

Overall validation

14. Overall trial validation is a logical AND of the following flags:
    - *a.* Gaze was found in the CS AOI.
    - *b.* Gaze was in the CS AOI at PS onset.
    - *c.* Gaze entered the PS AOI.
    - *d.* Missing data within the PS onset to PS gaze period was below criterion.
    - *e.* Gaze did not enter PS AOI before PS onset.
    - *f.* Gaze did not go in the opposite direction.
    - *g.* SRT was within bounds.

Trials that are false to any of these will be excluded from average scores.

Output variables

Output is written to an Excel file, with one row per subject * trial. Column headers are:

Variable	Description
CS_GAZE_MAX_GAP	Length of longest gap during CS gaze.
CS_GAZE_MAX_GAP_VALID	Flag for above
CS_GAZE	Flag: gaze within CS AOI

Variable	Description
CS_GAZE_AT_PS_ONSET_VALID	Flag: gaze was in CS AOI at PS onset
PS_GAZE	Flag: gaze entered PS AOI
MISS_VALID	Flag: no missing data
PS_EARLY_VALID	Flag: gaze not within PS AOI early
OPPOSITE_DIRECTION	Flag: gaze in the correct direction
SRT	Reaction time
SRT_VALID	Flag: SRT within bounds
CONDITION	Condition (1 = GAP, 2 = OVERLAP, 3 = BASELINE)
SIDE	PS side (1 = RIGHT, 2 = LEFT)
VALID	Flag: trial validation based on offline criteria

4c. Processing steps for the Anti-saccade Task

Offline trial classification

Gaze buffer is pre-processed to exclude gaze offscreen, interpolate data and average eyes.
Note that all Area of Interest (AOI) checking is done only on the x-axis. AOI is 2.5x the size of the original stimuli.

Sanity check (ensure this is a full trial, with uncorrupted data)

1. Check all relevant event markers are found.
2. Check the trial was not skipped by experimenter by looking at task log-file information
3. Find where target (TAR) was presented: left or right.

Gaze to Central Stimuli – ensure that gaze orient to CS

4. Find contiguous sections of gaze within the CS AOI, from the period of CS onset to DIS onset.
5. Find first contiguous section of gaze with length >24ms. Interpret this as orienting to the CS. Invalidate trial if no sections of gaze meet this criterion – *a*.
6. Look for a gap in the gaze data within the CS AOI either side of the DIS onset. Invalidate trial if gap is of length >100ms – *b*.

Gaze to TAR and DIS (Distractor)

7. Find if gaze entered the TAR AOI, from the onset of DIS. This is the first sample of the first contiguous section of gaze within the TAR AOI for at least 24ms (see step 4 and 5). Invalidate trial if no sections of gaze meet this criterion – c.
8. Find if gaze entered the DIS AOI, from the onset of DIS. This is the first sample of the first contiguous section of gaze within the DIS AOI for at least 24ms (see step 4 and 5).

Check if pro-saccade

9. If gaze orient to DIS (step 8) then check if event happened before TAR onset and before gaze orient to TAR (step 7) – this will define if a pro-saccade was made.
10. Check that gaze has not entered the DIS AOI for >50ms at DIS onset – *d*.
11. Calculate DIS Saccadic Reaction Time (SRT) as time from DIS onset to first sample of gaze in DIS AOI (see step 8).

Check if anticipatory saccade

12. Check if gaze on TAR happened before TAR onset – this will define if a anticipatory saccade was made.
13. Check that gaze has not entered the TAR AOI for >50ms at DIS onset – *e*.
14. Calculate TAR SRT as time from DIS onset to first sample of gaze in TAR AOI (see step 7).

Check missing gaps (ensure that gaze was on screen throughout trial)

15. Check gaps of missing data of length > 100ms from DIS onset to the moment gaze was found in TAR AOI. Invalidate trial if any found – *f*.

Overall validation

16. Overall trial validation is a logical AND of the following flags:
    - *a.* Gaze was found in the CS AOI.
    - *b.* Gaze was in the CS AOI at DIS onset.
    - *c.* Gaze was found in TAR AOI.
    - *d.* Gaze did not enter DIS AOI before DIS onset.
    - *e.* Gaze did not enter TAR AOI before DIS onset
    - *f.* Missing data within the DIS onset to TAR gaze period was below criterion.

Trials that are false to any of these will be excluded from average scores.

Output variables

Output is written to an Excel file, with one row per subject * trial. Column headers are:

Variable	**Description**
CS_GAZE	Flag: gaze within CS AOI
CS_GAZE_AT_DIS_ONSET_VALID	Flag: gaze was in CS AOI at DIS onset
TAR_GAZE	Flag: gaze entered TAR AOI
MISS_VALID	Flag: no missing data
DIS_EARLY_VALID	Flag: gaze not within DIS AOI early
TAR_EARLY_VALID	Flag: gaze not within TAR AOI early
DIS_SRT	Reaction time to DIS
TAR_SRT	Reaction time to TAR
PRO_SAC	Whether a pro-saccade was made (1 = pro-saccade

Variable	Description
	made)
ANTICIPATORY_SAC	Whether an anticipatory saccade was made (1 = anticipatory saccade made)
SIDE	TAR side (1 = LEFT, 2 = RIGHT)
VALID	Flag: trial validation based on offline criteria

4d. Results of the pre-registered analysis

The Gap-Overlap task

On the pre-registered 3.5 years longitudinal assessment plan effects in disengagement and facilitation in the Gap-overlap Task at 3.5 years were proposed to be tested in a repeated-measures ANOVA with effect type (disengagement, facilitation) as within subject factors and concurrent usage group (high, low) as between subject factor. The results of this pre-registered analysis were not similar to the ones reported with the GEE, see Appendix Table 7, due to the different analysis and independent variable used (main analysis tested longitudinal stable touchscreen use, and the pre-registered analysis was planned to test concurrent touchscreen use). At 3.5 years, there was a main effect of the type of effect measured in the task – this is just obvious given that the disengagement and facilitation are different in their direction (disengagement has a positive value, because overlap SRT > baseline SRT, whereas facilitation has a negative value, because gap SRT > baseline SRT). There was no other main effects or interactions in the pre-registered repeated-measures ANOVA. However, descriptively, high users tended to have a higher disengagement effect, as it was reported in the GEE – see Appendix Table 8.

Appendix Table 7. Summary statistics of the pre-registered repeated-measures ANOVA with type (disengagement, facilitation) as within subject factors and touchscreen usage group (high, low) as between factor, in the Gap-overlap Task at 3.5 years. The sample included 19 LUs and 26 HUs.

	Visit at 3.5 years
Pre-registered repeated-measures ANOVA: magnitude of effect	F (df_{IV}, df_{error}), p value
Effect type (disengagement, facilitation)	**110.914 (1,43), p < 0.001**
Group	2.519 (1,43), p = 0.120
Effect type*Group	0.098 (1,43), p = 0.756

Appendix Table 8. Mean and Standard Deviation of disengagement and facilitation effects in the Gap-Overlap Task, for each touchscreen use group at 3.5 years.

Visit at 3.5 years	Concurrent Touchscreen use group	Mean	SD
Disengagement	LU	96	77
	HU	118	83
Facilitation	LU	-44	58
	HU	-14	60

The Anti-saccade task

Effects in the Anti-saccade Task were meant to be examined using a t-test with proportion of anticipatory looks (i.e. any trial where the child looked at the target location before the onset of the target, or shortly after, up to 100 ms post-target onset) as the dependent variable and concurrent usage group (high, low) as the grouping variable. Results from this analysis did not show any significant difference between high and low users at 3.5 years in terms of proportion of anticipatory looks to the target location, $t(42) = 0.444$, $p = 0.659$ – see Appendix Table 9. These anticipatory looks measure includes corrective looks and anti-saccades, and thus the analysis presented in the main text, dissociating the various looking behaviours in the task, is a more suitable approach.

Appendix Table 9. Mean and Standard Deviation of proportion of anticipatory looks in the Anti-saccade, for touchscreen use group at 3.5 years, including 18 LUs and 26 HUs.

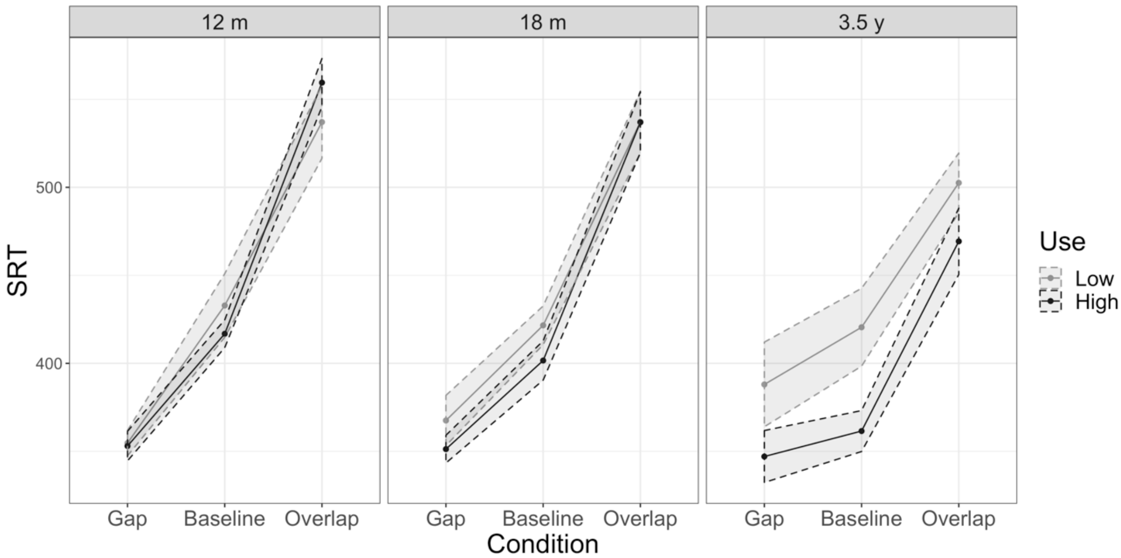
Visit at 3.5 years	Concurrent Touchscreen use group	Mean Proportion	SD
Anticipatory looks	LU	0.47	0.27
	HU	0.44	0.21

4e. Mean and Standard Deviation of Saccadic Reaction Time in the Gap-Overlap Task

Appendix Table 10. Mean and Standard Deviation of Saccadic Reaction Time in milliseconds of each trial condition in the Gap-Overlap Task, for each Longitudinal touchscreen use group at each age point.

Age	Condition	Longitudinal touchscreen use group	Mean SRT	SD
12 months	Baseline	HU	417	40
		LU	433	68
	Gap	HU	353	43
		LU	355	27
	Overlap	HU	559	70
		LU	537	77
18 months	Baseline	HU	402	53
		LU	422	41
	Gap	HU	351	38

Age	Condition	Longitudinal touchscreen use group	Mean SRT	SD
		LU	368	53
	Overlap	HU	537	83
		LU	537	66
3.5 years	Baseline	HU	362	51
		LU	421	83
	Gap	HU	347	64
		LU	388	90
	Overlap	HU	469	82
		LU	503	63



*Appendix Figure 2. Mean Saccadic Reaction Time (ms) for each Longitudinal touchscreen use group as a function of trial condition in the Gap-Overlap Task and age (12 months, 18 months, and 3.5 years). Shaded areas represent standard error of the mean. *p < 0.05.*

4f. Mean and Standard Deviation of Proportion of look behaviour in the Anti-saccade Task

Appendix Table 11. Mean and Standard Deviation of proportion of each saccadic behaviour in the Anti-Saccade Task for each half of the task and age point.

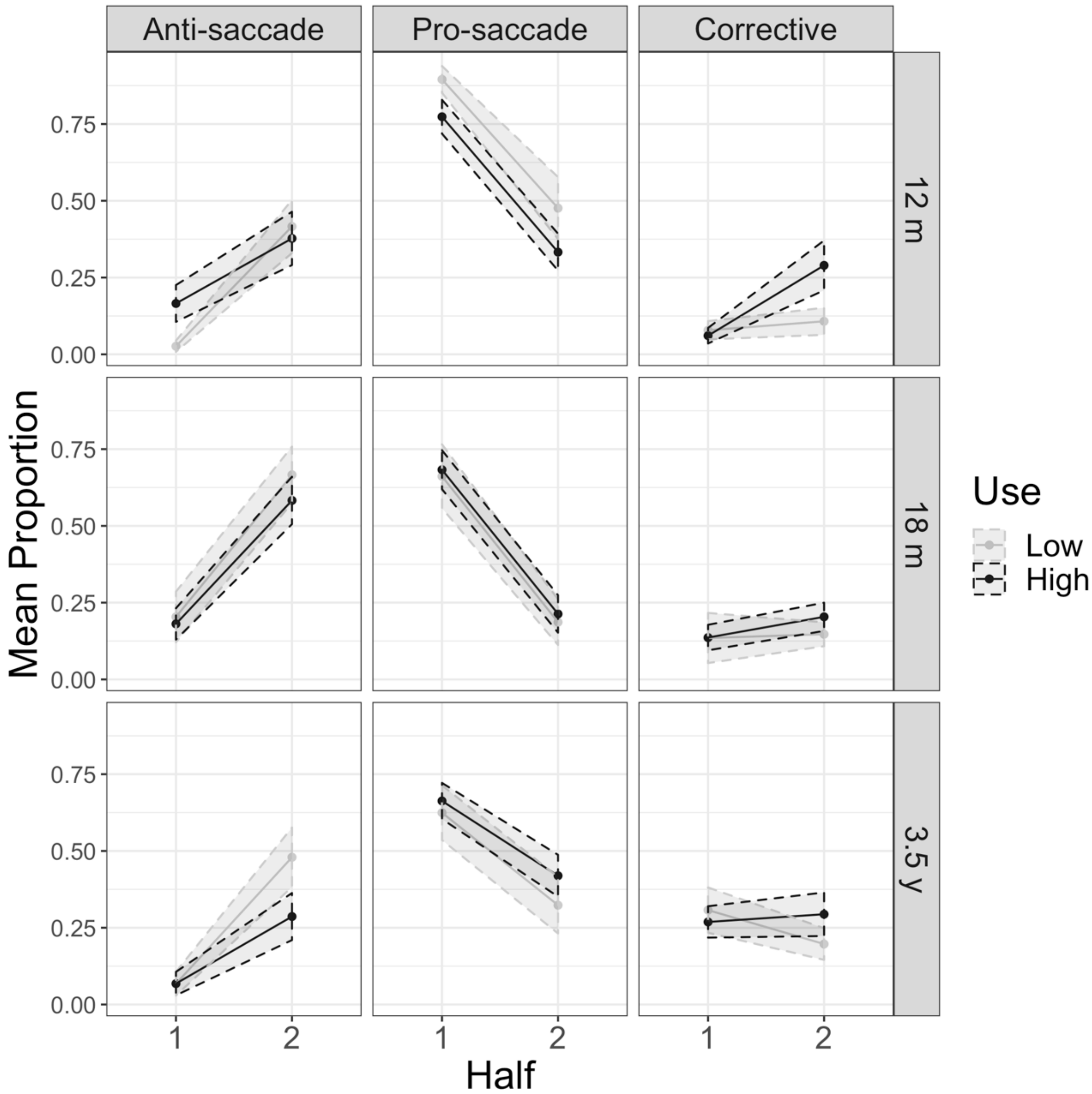
Type	Age	Half	Mean %	SD
Anti-saccade	12 months	1	0.11	0.21
		2	0.39	0.34
	18 months	1	0.19	0.25
		2	0.61	0.34
	3.5 years	1	0.07	0.15
		2	0.36	0.35
Pro-saccade	12 months	1	0.82	0.21
		2	0.39	0.31
	18 months	1	0.68	0.32

Type	Age	Half	Mean %	SD
		2	0.20	0.27
	3.5 years	1	0.65	0.28
		2	0.38	0.31
Corrective looks	12 months	1	0.07	0.11
		2	0.21	0.29
	18 months	1	0.14	0.23
		2	0.18	0.19
	3.5 years	1	0.28	0.24
		2	0.25	0.27

Appendix Table 12. Mean and Standard Deviation of proportion of each saccadic behaviour in the Anti-Saccade Task for each half of the task, Longitudinal touchscreen use group, and age point.

Age	Type	Half	Longitudinal touchscreen use group	Mean %	SD
12 months	Anti-saccade	1	HU	0.17	0.25
			LU	0.03	0.07
		2	HU	0.38	0.37
			LU	0.42	0.31
	Corrective look	1	HU	0.06	0.11
			LU	0.08	0.11
		2	HU	0.29	0.34
			LU	0.11	0.16
	Pro-saccade	1	HU	0.77	0.23
			LU	0.90	0.16
		2	HU	0.33	0.25
			LU	0.48	0.36
18 months	Anti-saccade	1	HU	0.18	0.24
			LU	0.20	0.29
		2	HU	0.58	0.36
			LU	0.67	0.32
	Corrective look	1	HU	0.14	0.19
			LU	0.13	0.28
		2	HU	0.20	0.22
			LU	0.15	0.13
	Pro-saccade	1	HU	0.68	0.30
			LU	0.66	0.36
		2	HU	0.21	0.29
			LU	0.19	0.26
3.5 years	Anti-saccade	1	HU	0.07	0.17
			LU	0.07	0.14
		2	HU	0.29	0.33
			LU	0.48	0.35

Age	Type	Half	Longitudinal touchscreen use group	Mean %	SD
	Corrective look	1	HU	0.27	0.22
			LU	0.31	0.27
		2	HU	0.29	0.31
			LU	0.20	0.19
	Pro-saccade	1	HU	0.66	0.26
			LU	0.62	0.32
		2	HU	0.42	0.30
			LU	0.32	0.33



Appendix Figure 3. Mean Proportion for each Longitudinal touchscreen use group (N=38) as a function of Task Half and look behaviour in the Anti-Saccade Task and age (12 months, 18 months, and 3.5 years). Shaded areas represent standard error of the mean.

4g. Mean and Standard Deviation of Saccadic Reaction Time in the Anti-saccade Task

Appendix Table 13. Mean and Standard Deviation of Saccadic Reaction Time in milliseconds to the distractor (during a pro-saccade) and to the target (during an anti-saccade) in the Anti-Saccade Task, for each Longitudinal touchscreen use group.

Direction	Longitudinal touchscreen use group	Mean SRT	SD
To distractor (during a pro-saccade)	LU	535	154
	HU	480	129
To Target location (during an anti-saccade)	LU	642	248
	HU	700	244

Appendix Table 14. Mean and Standard Deviation of Saccadic Reaction Time in milliseconds to the distractor (during a pro-saccade) and to the target (during an anti-saccade) in the Anti-Saccade Task, for each Longitudinal touchscreen use group at each age point.

Age	Direction	Longitudinal touchscreen use group	Mean SRT	SD
12 months	To distractor (during a pro-saccade)	HU	518	106
		LU	538	104
	To Target location (during an anti-saccade)	HU	749	281
		LU	677	272
18 months	To distractor (during a pro-saccade)	HU	522	149
		LU	600	197
	To Target location (during an anti-saccade)	HU	661	232
		LU	551	186
3.5 years	To distractor (during a pro-saccade)	HU	409	96
		LU	481	149
	To Target location (during an anti-saccade)	HU	709	217
		LU	722	271

4h. Results covarying for Background TV and gender

Appendix Table 15. Summary of GEE models including half, group, and age as predictors of proportion and latency of saccadic behaviour in the Anti-saccade Task when adding background TV or gender or as covariates. Only models where the covariate had a significant main effect are shown. The analysis included 14 LUs and 24 HUs.

	Background TV as covariate Wald χ^2 (df), p value	***Gender as covariate*** Wald χ^2 (df), p value
% Anti-saccades		
Half	**121.162 (1), p < 0.001**	
Age	**10.495 (2), p = 0.005**	
Group	0.327 (1), p = 0.567	
Covariate	**9.666 (1), p = 0.002**	
Half**Group*	**4.574 (1), p = 0.032**	
Age**Group*	1.465 (2), p = 0.481	
Half*Age	3.327 (2), p = 0.189	
Half*Age**Group*	0.808 (2), p = 0.668	

	Background TV as covariate Wald χ^2 (df), p value	***Gender as covariate*** Wald χ^2 (df), p value
% Pro-saccades		
Half	**256.775 (1), p < 0.001**	
Age	**8.546 (2), p = 0.014**	
Group	0.247 (1), p = 0.619	
Covariate	**5.615 (1), p = 0.018**	
Half*Group*	0.102 (1), p = 0.75	
Age*Group*	1.782 (2), p = 0.41	
Half*Age	**11.102 (2), p = 0.004**	
Half*Age*Group*	0.173 (2), p = 0.917	
% Corrective looks		
Half	3.158 (1), p = 0.076	
Age	**9.73 (2), p = 0.008**	
Group	0.365 (1), p = 0.546	
Covariate	**11.997 (1), p = 0.001**	
Half*Group*	**4.251 (1), p = 0.039**	
Age*Group*	0.123 (2), p = 0.94	
Half*Age	**6.16 (2), p = 0.046**	
Half*Age*Group*	1.413 (2), p = 0.493	
SRT to distractor (pro-saccade)		
Half	0.013 (1), p = 0.910	
Age	**14.891 (2), p = 0.001**	
Group	**3.872 (1), p = 0.049**	
Covariate	1.714 (1), p = 0.190	
Half*Group*	0.768 (1), p = 0.381	
Age*Group*	2.178 (2), p = 0.336	
Half*Age	5.872 (2), p = 0.053	
Half*Age*Group*	2.813 (2), p = 0.245	
SRT to target location (anti-saccade)		
Half	**4.232 (1), p = 0.04**	**11.146 (1), p = 0.001**
Age	**22.396 (2), p < 0.001**	**51.728 (2), p < 0.001**
Group	1.220 (1), p = 0.269	0.213 (1), p = 0.645
Covariate	**9.289 (1), p = 0.002**	**5.15 (1), p = 0.023**
Half*Group*	1.265 (1), p =0.261	2.619 (1), p = 0.106
Age*Group*	0.252 (2), p = 0.881	0.366 (2), p = 0.833
Half*Age	4.36 (2), p = 0.113	3.403 (2), p = 0.182
Half*Age*Group*	0.273 (2), p = 0.872	0.902 (2), p = 0.637

4i. GEE Model effects on the Gap SRT of the Gap-Overlap Task

Appendix Table 16. GEE Model effects including longitudinal user group and age as predictors of the Gap condition SRT. The analysis included 14 LUs and 26 HUs.

	Longitudinal usage group model Wald χ^2 (df), p value
Follow-up model on Gap SRT	
Age	0.53 (2), p = 0.767
Group	1.995 (1), p = 0.158
Age*Group*	1.695 (2), p = 0.428

5. *Chapter 5 Appendix*

5a. Exploratory factor analysis: factor loadings

Appendix Table 17. Factor loadings based on an exploratory factor analysis with 1 factor and 8 items from the EF battery of the 3.5 years TABLET visit (N=46).

	Factors
	1.
Delayed Alternation WM Score	0.58
Spin the pots Score	
DCCS Switchers	
Go/No-Go % Omission Errors	
Go/No-Go Low Control	-0.50
Anti-saccade % 2nd Half	
Snack Delay Sum Score	0.42
Glitter Wand High Control	0.83
CBQ Inhibitory Control Score	

**Factor loadings ≤.3 are supressed.*
Method of extraction = WLSMV, Type of rotation = oblique.

Appendix Table 18. Factor loadings based on an exploratory factor analysis with 2 factors and 8 items from the EF battery of the 3.5 years TABLET visit (N=46).

	Factors	
	1.	2.
Delayed Alternation WM Score		0.78
Spin the pots Score		0.36
DCCS Switchers	-0.37	0.63
Go/No-Go % Omission Errors		
Go/No-Go Low Control	-0.39	
Anti-saccade % 2nd Half		
Snack Delay Sum Score	0.57	
Glitter Wand High Control	0.95	
CBQ Inhibitory Control Score		

**Factor loadings ≤.3 are supressed.*
Method of extraction = WLSMV, Type of rotation = oblique.

5b. Exploratory associations between EF and attention control measures

Appendix Table 19. Results from binary logistic regression with attention control (disengagement on the Gap-overlap Task and Visual Search single search reaction time) entered in a single step to predict DCCS performance and Go/No-go performance. Disengagement at 18 months was a significant predictor of DCCS performance, in a way that a reduced disengagement was associated with a successful switch in the DCCS.

Attention control measures	**DCCS Switchers** Wald χ^2 (df), p value, Exp (B) N	**Go/No-Go Low Control** Wald χ^2 (df), p value, Exp (B) N
At 18 months		
Endogenous: Disengagement	**5.698 (1), 0.017** **0.982** **38**	0.055 (1), 0.815 1.001 31
Exogenous: Single Search RT	1.106 (1), 0.293 0.221 38	0.908 (1), 0.341 0.171 31

Attention control measures	**DCCS Switchers** Wald χ^2 (df), p value, Exp (B) N	**Go/No-Go Low Control** Wald χ^2 (df), p value, Exp (B) N
At 3.5 years		
Endogenous: Disengagement	0.574 (1), 0.449 0.997 43	0.224 (1), 0.636 1.002 35
Exogenous: Single Search RT	0.462 (1), 0.497 1.948 43	2.41 (1), 0.121 0.095 35