

Brain activations related to attention and working memory and their association with technology-mediated activities

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Academic dissertation to be publicly discussed,
by due permission of the Faculty of Medicine
at the University of Helsinki in Auditorium K170, Siltavuorenpenger 1A,
on the 31st of March, 2017, at 12 o'clock

ISSN 2342-3161 (Print)

ISSN 2342-317X (Online)

ISBN 978-951-51-2979-6 (pbk)

ISBN 978-951-51-2980-2 (PDF)

Unigrafia

Helsinki 2017

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ABSTRACT

Executive functions are pivotal in our everyday lives, as they form the basis for complex and goal-directed behavior. For example, the ability to maintain information in memory while making a decision requires executive processes. Whether or not executive functions can exhibit experience-dependent changes is still a topic of debate, but generally accepted principles of brain plasticity suggest that environmental factors can have an impact on cognitive processes and the activity and structure of their respective brain networks. One such environmental factor is the increasingly ubiquitous daily interaction with technology, which has been suggested to affect mental faculties such as the ability to maintain focus on a single task or to actively maintain information in short-term memory.

The aim of the present thesis was to study activity in cortical networks of attention and working memory. In addition, we investigated whether any associations could be found between the recruitment of these networks or performance speed and accuracy in working memory and attention tasks, and the extent of daily technology-mediated activities reported by adolescent and young adult participants. In all studies, functional magnetic resonance imaging (fMRI) was used to record brain activity during task performance.

By using novel experimental paradigms, the present results shed more light on the specific cortical networks recruited by different executive functions by showing that both common and specific brain regions are recruited by auditory and visual selective attention, divided attention and working memory processes. Furthermore, they demonstrate that during division of attention between two concurrent tasks (listening to speech and reading text), competition for neural resources in regions shared by the component tasks is a major contributor to performance limitations observed during multitasking. Importantly, the results of the present thesis also demonstrate that detectable associations exist between different types of daily technology use and cognitive functioning already in adolescence. More specifically, the results demonstrate that a tendency to use several media simultaneously (i.e., *media multitasking*) is related to increased distractibility. The extent of computer gaming in daily life, in turn, is associated with enhanced working memory functioning. These findings are of great importance, since it is vital to understand how the increasing amount of on-screen time might affect or interact with the cognitive and brain functioning of the current youth.

TIIVISTELMÄ

Toiminnanohjaus käsittää joukon toimintoja, jotka mahdollistavat tavoitteellinen ja monimutkaisen toiminnan jokapäiväisissä tilanteissa. Esimerkki toiminnanohjauksesta on kyky ylläpitää tietoa muistissa samalla kun tekee päätöksen. On edelleen epäselvää, kuinka suuri vaikutus kokemuksella voi olla toiminnanohjaukseen lukeutuviin toimintoihin, mutta yleisesti hyväksytyt aivojen muovautuvuuteen liittyvät periaatteet antavat syyn olettaa, että ympäristötekijöiden on mahdollista vaikuttaa kognitiiviseen suoriutumiseen ja niihin liittyviin aivoverkostoihin. Jatkuvasti lisääntyvä teknologian parissa vietetty aika on yksi niistä ympäristötekijöistä, joiden on ehdotettu vaikuttavan kognitiivisiin toimintoihin kuten kykyyn keskittyä yhteen tehtävään samanaikaisesti, tai kykyyn ylläpitää tietoa lyhytkestoisessa muistissa.

Tässä esitellyn väitöskirjatyön tavoite oli tutkia tarkkaavaisuuteen ja työmuistiin liittyviä aivoverkostoja. Lisäksi selvitettiin sitä, onko näiden aivoverkostojen toiminnalla ja tarkkaavaisuus- ja työmuistitehtävissä suoriutumisella yhteyksiä nuorten ja nuorten aikuisten itseraportoituihin teknologiankäyttötapoihin. Kaikissa väitöskirjan osatutkimuksissa käytettiin toiminnallista magneettiresonanssikuvantamista (fMRI) mittaamaan aivojen aktivoitumista tehtäväsuorituksen aikana.

Käyttämällä uusia ja innovatiivisia koeasetelmia, tutkimuksemme tulokset tuottivat lisää tietoa eri toiminnanohjaukseen liittyvien toimintojen aktivoimista aivoverkostoista näyttämällä, että valikoiva tarkkaavaisuus, jaettu tarkkaavaisuus ja työmuistiprosessit aktivoivat sekä yhteisiä että erillisiä aivoalueita. Lisäksi tuloksemme osoittivat, että jaettaessa tarkkaavaisuutta kahden samanaikaisen tehtävän kesken, kilpailu hermostollisista resursseista näiden kahden samaa aivoaluetta kuormittavan tehtävän välillä vaikuttaa oleellisesti ihmisen rajalliseen monisuorittamiskykyyn. Tuloksemme osoittavat myös, että päivittäisten teknologian käyttötapojen ja kognitiivisen suoriutumisen välillä on havaittavia yhteyksiä jo nuoruusiässä. Taipumus käyttää montaa mediaa samanaikaisesti (nk. *media multitasking*) oli yhteydessä suurempaan häiriintyvyyteen, kun taas tietokonepelien pelaaminen oli yhteydessä parempaan työmuistisuoriutumiseen. Nämä tulokset ovat erittäin merkityksellisiä, sillä on tärkeää ymmärtää, minkälaisia mahdollisia vaikutuksia nuorten alati kasvavalla ruutuajalla on heidän kognitiivisiin toimintoihinsa ja aivojen toimintaan.

ACKNOWLEDGEMENTS

First and foremost, I wish to thank my supervisors, Professor Kimmo Alho and Docent Viljami Salmela. I am grateful for having had the opportunity to carry out the studies of the current thesis under your supervision in the Attention and Memory Networks (AMN) research group at the University of Helsinki. I have been extremely lucky to have had two such incredible supervisors, who have always been available for help and support. I cannot thank you both enough for all of the guidance and encouragement you have given me during the past four years. I also express my gratitude to the entire research team of AMeN, including Emma Salo and Docent Juha Salmitaival.

I am also grateful for having had the opportunity to work and be funded by the Mind the Gap project at the Faculty of Teacher Education, University of Helsinki. Without the Mind the Gap project, this thesis would not exist. It has been such a pleasure and quite a joyride to have had worked in this project. I wish to thank all of the talented young researchers working in this project, as well as the three Professors: Kirsti Lonka, Katariina Salmela-Aro and Kai Hakkarainen. You are all inspirational examples of what it means to be an ambitious and successful researcher while always remaining kind and amicable and to others. In addition to the Mind the Gap project, this thesis work was funded by Eemil Aaltonen foundation and the Jenny and Antti Wihuri foundation. Thanks to them, I have been able to work as a full-time doctoral student during my thesis work, for which I am grateful.

The data of the present studies were collected at the Advanced Magnetic Imaging (AMI) Centre, Aalto University. I wish to thank all of the employees of AMI Center for their patience during our seemingly endless and nerve wracking data gathering phase. I would like to extend special thanks to Marita Kattelus, Tuomas Tolvanen and Toni Auranen for their help and expertise. A warm thank you also goes to the research assistants Mari Räsänen, Janne Illi, Ilkka Muukkonen and Tessa Tolonen for their help with participant recruitment and measurements.

I am grateful to Professor Synnöve Carlson for all of her help with conducting the measurements at AMI, and for never being too busy to comment on articles and posters even on short notice. I am also very grateful to my other co-authors: Lauri Hietajärvi, Professor Oili Salonen and Dr. Virve Vuontela for our fruitful collaboration. I also wish to thank Jari Lipsanen and Dr. Markku Verkasalo for their help with all things statistics. My warmest thanks also go to Dr. Otto Lappi for encouraging me to aspire to do good science. I also extend the warmest thanks to Professor Emerita of Cognitive Science, Christina Krause, for giving me my first academic job, and for later on managing to convince Professor Alho that it was a good idea to hire me. I also want to thank the official reviewers of this thesis, Professor Sonja A. Kotz and Docent Iiro Jääskeläinen for constructive comments on

the manuscript, and for Professor Lars Nyberg for agreeing to serve as my opponent.

I wish to thank all of the young colleagues at the University that I have had the pleasure to meet throughout the years. I thank the researchers of NuTu for the much needed peer support. I would especially like to thank Dr. Michael Laakasuo for being my spiritual mother hen and for guiding me onto a path of change and growth. My thanks also go out to my beautiful, dear friends who have helped me take my mind off work, and who I am extremely grateful to have by my side.

I am deeply grateful to my mother Teija Moisala, father Aarni Moisala, sisters Jenna and Isabel Moisala, as well as to my extended family Timo Kervinen, Tapio Hulkkonen, Ann-Marie Mattson, Sebastian Liljelund and Rauni-Mari Ketomäki for all their encouragement and support. I know that I may have (occasionally) worked (a little bit) too much, so thank you for being patient with me! I am especially grateful for the opportunity to vent about all things academic and non-academic to my dear sister Jenna, whose intellectual curiosity and enthusiasm are admirable. I am also thankful to Eemil, Milja and Joel Kervinen for all of the joy they bring into my life. I thank my grandmother Auli Tornberg for all her love and support. I wish all of my grandparents could have been here to witness the completion of my doctoral studies. I would like to dedicate this thesis to my dear Pepe-vaari. Finally, with overwhelming gratitude, I thank my karhumies and my dear husband, Niko Liljelund. Thank you for being my biggest supporter, my love and my light, and most of all, my trusted partner in life. Thank you for reminding me when I needed it the most that: “It’s just a ride!”

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

- Study I** **Moisala, M.**, Salmela, V.R., Salo, E., Carlson, S., Vuontela, V., Salonen, O., & Alho, K. (2015). Brain activity during divided and selective attention to auditory and visual sentence comprehension tasks. *Frontiers in Human Neuroscience*, 9, 86.
- Study II** **Moisala, M.**, Salmela, V., Hietajärvi, L., Salo, E., Carlson, S., Salonen, O., Lonka, K., Hakkarainen, K., Salmela-Aro, K., & Alho, K. (2016). Media multitasking is associated with distractibility and increased prefrontal activity in adolescents and young adults. *NeuroImage*, 134, 113-121.
- Study III** **Moisala, M.**, Salmela, V., Hietajärvi, L., Carlson, S., Vuontela, V., Lonka, K., Hakkarainen, K., Salmela-Aro, K., & Alho, K. (2016) Gaming is related to enhanced working memory performance and task-related cortical activity. *Brain Research*, 1655, 204–215.

ABBREVIATIONS

ANOVA	Analysis of variance
BOLD	Blood-oxygen-level-dependent
DA	Digital activity
EEG	Electroencephalography
EPI	Echo planar imaging
fMRI	Functional magnetic resonance imaging
GPA	Grade point average
IFG	Inferior frontal gyrus
MEG	Magnetoencephalography
MFG	Middle frontal gyrus
MMT	Media multitasking
MR	Magnetic resonance
MRI	Magnetic resonance imaging
PET	Positron emission tomography
ROI	Region of interest
SMA	Supplementary motor area
SDP	Sociodigital participation
SFG	Superior frontal gyrus
SPL	Superior parietal lobule
Prc	Precuneus

1 INTRODUCTION

The ability to pay attention to relevant features in the environment while ignoring distractors, or the ability to maintain several pieces of information in memory while making a decision are both examples of cognitive functions that are vital to an individual's survival. Such faculties are especially well developed in humans, allowing us to behave in purposeful and goal-directed manner even in unfamiliar situations (Diamond, 2013). The neural networks of the human brain that underlie these complex abilities are generally thought to consist of frontal and parietal cortical regions (Badre & D'Esposito, 2007; Vincent et al., 2008), where higher level cognitive functions activate both common and specific areas of the brain (Friedman & Miyake, 2016). Frontoparietal regions continue to develop postnatally throughout adolescence (Gogtay et al., 2004; Squeglia et al., 2013), allowing for cognitive performance to refine and improve as one reaches mature adulthood. Genetics play an important role in how the cortical networks mature both in terms of structure (Blokland et al., 2012; Thompson et al., 2001) and functional connectivity (Glahn et al., 2010), but importantly, the development of brain networks is also shaped by experience. For example, long-term meditation practice has been shown to affect both brain connectivity (Jang et al., 2011) and cortical gray matter volume (Lazar et al., 2005). However, environmental factors that can influence brain structure and function are not limited only to scheduled and planned exercises such as meditation, but extend to many other types of activities that are repeated often enough in daily life. One such environmental factor may be the extensive use of technology in daily life. It has been suggested that the introduction of the Internet age and portable technological devices such as smartphones may shape human cognition, as such a large portion of the day is spent interacting with these technologies in Western developed countries (Carr, 2010; Loh & Kanai, 2015). Young people may be especially susceptible to the possible effects of technology, because they have been immersed in digital technologies from very early in their lives (Prensky, 2001), and because their brains are still undergoing substantial development and are presumably therefore more malleable than a fully mature adult brain (Gogtay et al., 2004; Squeglia et al., 2013).

The present **Studies I, II** and **III** give insight into the cortical networks of attention and working memory, and examine how activity in these networks and performance in attention-demanding and working-memory tasks are related to daily technology-mediated activities in adolescents and young adults. We identified the cortical networks recruited by selective and divided attention in adult participants in **Study I**. In **Study II** and **Study III**, we investigated in adolescent and adult participants the relationship between self-reported daily media multitasking activity and attentional abilities and task-related cortical activity (**Study II**), as well as the relationship between computer gaming activities and working memory

performance and the recruitment of task-relevant cortical regions (**Study III**).

1.1 Executive functions

Executive functions allow us to coordinate and control our behavior (Luria, 1966), and they refer to a collection of mental processes needed to function in non-routine and complex situations (Diamond, 2013). Although all executive functions share a common feature related to cognitive control so that one unitary subordinate system could be inferred (Niendam et al., 2012), low correlations between different executive tasks imply that executive functions form a collection of top-down mental processes which are at least partly distinguishable (Duncan et al., 1997; Shallice & Burgess, 1996). Three core executive functions are most commonly postulated: inhibition (including behavioral inhibition, selective attention and cognitive inhibition), monitoring and updating of working memory representations, and cognitive flexibility or set shifting (e.g., Lehto et al. 2003, Miyake et al. 2000).

A diverse set of brain regions is involved in executive functions and cognitive control, but it is commonly held that a “frontoparietal control network” is crucial to these processes (Badre & D’Esposito, 2007; Vincent et al., 2008), comprising of the rostralateral prefrontal cortex, middle frontal gyrus, anterior insula, dorsal anterior cingulate cortex, precuneus, and anterior inferior parietal lobule. It has been suggested that this network could also be referred to as a “multiple-demand system”, as it is activated by a variety of demanding cognitive tasks that require the formation of a series of subtasks (Duncan, 2010). The prefrontal cortex has a crucial role in cognitive control (Miller & Cohen, 2001), as demonstrated by both the effects of prefrontal lesions on behavior (e.g., Owen et al., 1996) as well as prefrontal activations in brain imaging studies (e.g., Koechlin et al., 1999; Smith & Jonides, 1999). Human ontogeny and phylogeny also point to the special role of the frontal lobes in human cognitive development. The human prefrontal cortex matures postnatally throughout adolescence (Gogtay et al., 2004; Squeglia et al., 2013), which is thought to underlie the improvement in attention and working memory performance observed during this time (Casey et al., 2000). Evidence from comparative studies of existing species leads to the conclusion that during human evolution, the prefrontal cortex has grown disproportionately more than other cortical regions (Fuster, 2002).

The following sections will focus on two aspects of executive functioning relevant to the current thesis: attention and working memory.

1.1.1 Selective and divided attention

“Everyone knows what attention is. It is taking possession of the mind, in clear and vivid form, of one out of what seems several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies a withdrawal from some things in order to deal effectively with others.”

-William James (1890, pp.403-404)

Attention refers to a theoretical concept used to describe how one or more aspects of the internal or external environment is under more detailed inspection, so that the target of attention can vary from a simple feature to a complex object, and the focus of attention can vary from broad to narrow (Näätänen, 1992). Selective attention refers more specifically to the process of selecting an object for further processing while ignoring unattended stimuli, so that the unattended stimuli receive far less processing than the attended ones (Broadbent, 1958; Lachter et al., 2004). In the auditory modality, selective attention has often been studied using the *dichotic listening paradigm* (Cherry, 1953), where different auditory inputs are presented to the left and right ear and the listener is asked to selectively attend only to the input delivered to a designated ear. Brain imaging studies have often utilized the dichotic listening paradigm to study the brain mechanisms of auditory selective attention, so that attended and unattended stimuli have differed from each other in features such as pitch, location, or intensity. Auditory selective attention has been studied using electroencephalography (EEG; e.g., Hillyard et al., 1973, Näätänen et al., 1978; for a review, see Alho, 1992), magnetoencephalography (MEG; e.g., Degerman et al., 2008; Hari et al., 1989, Woldorff et al., 1993), positron emission tomography (PET; e.g., Alho et al., 1999, Tzourio et al., 1997, Zatorre et al., 1999) and functional magnetic resonance imaging (fMRI; e.g., Degerman et al., 2007; Hill & Miller, 2010; Janata et al., 2002; Salmi et al., 2007). In the visual modality, the brain mechanisms of selective attention are often studied using the *covert attention paradigm* (e.g., Corbetta et al., 1993; Heinze et al., 1994; Hopf & Mangun, 2000; Martinez et al., 2006; Noesselt et al., 2002). In this paradigm, the participant fixes their gaze on one location of the stimulus and attends to another location. Stimuli may then be presented in the unattended locations, and neural activity related to the processing of attended and unattended stimuli can be compared.

Brain imaging studies have demonstrated that selective attention is characterized by the recruitment of more posterior cortical regions, so that the location of enhanced activity is influenced by the specific attributes that are attended to (Corbetta et al., 1990). This has been demonstrated for selective attention to sounds with a particular pitch or location (Alho et al., 2006; Pugh et al., 1996; Woodruff et al., 1996; for a review, see Alho et al.,

2014), or to the color (Clark et al., 1997) or motion of visual stimuli (Beauchamp et al., 1997), so that activity in posterior regions specialized in processing the respective attributes show heightened activity during selective attention. It is thought that prefrontal and parietal regions mediate the activity modulation seen in the more posterior cortical regions (Alho et al., 1999; Heinze et al., 1994; Rees et al., 1997; Zatorre et al., 1999).

When two or more objects are attended to simultaneously or when two tasks are performed in parallel, the term divided attention or multitasking is used. The experimental paradigms for studying divided attention have used highly varying component tasks. For example, in the study by Adcock and colleagues (2000), participants listened to nouns and responded to nouns in pre-specified semantic categories while performing a visual mental rotation task or a face identification task simultaneously. Salo and colleagues (2015), in turn, compared different combinations of dual tasks, where participants had to identify targets simultaneously in streams of letters and spoken syllables based on, for example, their phonetic characteristics or presentation location. In the study by Johnson and Zatorre (2005), participants were presented with concurrent melodies and abstract shapes unfolding over time, and had to detect long notes in the melodies while detecting vertical line segments in the shapes.

Dividing attention between several simultaneous objects is demanding and decrements in performance speed and accuracy are often seen in multitasking situations (Pashler, 1994). These performance decrements may be due to a bottleneck in specialized systems of executive task-coordination that are recruited only during multitasking (D'Esposito et al., 1995; Collette et al., 2005). An additional source of interference may emerge if the component tasks are presented in different sensory modalities and the corresponding sensory cortices have to compete for attentional resources (e.g., Näätänen, 1992), or if the brain areas related to carrying out the component tasks in case component tasks require similar (e.g., phonological or spatial) processing (Saló et al. 2015). The coordination of multiple parallel tasks during divided attention has been shown to recruit specific frontal and parietal cortical regions. In the frontal lobe, the inferior (Herath et al., 2001; Schubert & Szameitat, 2003; Stelzel et al., 2006), middle (Szameitat et al., 2002; Yoo et al., 2004) and the superior lateral prefrontal regions (Corbetta et al., 1991; D'Esposito et al., 1995; Johnson & Zatorre, 2005) have been shown to be highly active during divided attention. In the parietal cortex, multitasking regions include the superior parietal lobule (Degerman et al., 2007; Yoo et al., 2004) and intraparietal sulcus (Szameitat et al., 2002). Some studies have, however, failed to show multitasking-related activity in areas beyond those activated by the component tasks (Klingberg, 1998; Adcock et al., 2000; Bunge et al., 2000; Nijboer et al., 2014), thus questioning the existence of specialized multitasking regions. The specific pattern of frontoparietal recruitment has also been shown to vary according to the specific task demands of the component tasks (Saló et al., 2015). It

therefore still remains unclear, whether the main factor limiting performance during multitasking is the involvement of coordinating or executive functions, or whether limited task-specific resources are responsible for the observed interference during multitasking.

1.1.2 Working memory

The concept of working memory refers to a system responsible for both short-term storage and manipulation of information in the mind. It serves both to encode new information from sensory memory buffers and to retrieve memories from long-term memory (Baddeley & Hitch, 1974). The main function of working memory is to maintain memory representations active while other cognitive processing takes place, and it therefore plays an important role in complex cognition (Baddeley, 1996).

There are several different ways of conceptualizing working memory, and they may vary between different academic disciplines (Shah & Miyake, 1999). According to the classical multicomponent model of working memory introduced by Baddeley and Hitch (1974), working memory consists of three separate components: a phonological loop which processes auditory and phonological information, a visuospatial sketch pad which processes visual and spatial information, and a central executive which controls the two previous systems. Baddeley (2000) later added a fourth component to the model: an episodic buffer that transmits information between long-term memory and the central executive. Working memory models that diverge from this classical model have also been proposed, and the structure of working memory therefore still remains controversial. For example, Cowan (1997) formulated an alternative but partly overlapping model where working memory is seen as a part of long term memory activated by attentional focus. In this model, short-term memory holds information that has been activated in long-term memory, and the central executive controls which part of this activated information is then selected to be in the focus of attention. Cowan's model therefore combines the concepts of working memory and attention.

Working memory is generally agreed to have limited capacity, but the origin of these memory limitations is still under debate. According to the classical models, the visual and auditory modalities have separate stores for the short-term maintenance of information (Baddeley & Hitch, 1974), and a general, attentional limit of three or four objects exists (Cowan, 2001). More recently, a resource based working memory model has gained support as well, with cumulative evidence from both visual (e.g., Bays & Husain, 2008) and auditory (e.g., Kumar et al., 2013) studies. These studies posit that memory capacity is limited due to the precision, and not to the number, of working memory representations, and that limited resources affect memory precision across sensory modalities (e.g., Salmela et al., 2014).

One of the most popular experimental paradigms for studying the neural basis of working memory has been the n -back task. In this task, the participant is required to report whether a presented stimulus matched a stimulus presented n trials previously, where n is a prespecified integer (usually 1, 2 or 3). With this paradigm, the load placed on working memory may therefore be varied by increasing the size of the n integer while keeping all other features of the stimuli constant (Braver et al., 1997; Carlson et al., 1998). Various input modalities and target features (i.e., the feature used to match targets) have been used, thus placing demands on different processing modalities. The n -back task is thought to tax several key processes within working memory, as it requires on-line monitoring, updating, and manipulation of information (Owen et al., 2005). By increasing the delay time between successive stimuli, the different phases of memory (i.e., encoding, maintenance, and retrieval) can also be studied (Cohen et al., 1997). Brain imaging studies utilizing the n -back paradigm have demonstrated that a distributed cortical network comprising of both dorsolateral prefrontal and parietal regions are consistently activated during this task irrespective of the target feature used in the study (Carlson et al., 1998; Cohen et al., 1997; Martinkauppi et al., 2000; Rämä et al., 2001), so that prefrontal activity has been shown to increase linearly with the level of working memory load (Braver et al., 1997; Cohen et al., 1997). Working memory functioning in general is thought to involve fronto-parietal regions (Cabeza & Nyberg, 1997; Cabeza & Nyberg, 2000), so that a circuitry of re-entrant loops between these regions would be crucial for the sustained attention processes needed to actively maintain information in working memory (Eriksson et al., 2015). Although all n -back versions broadly activate the same frontal and parietal cortical regions, the specific attributes of the n -back tasks are associated with subregional differences in activation patterns. For example, for linguistic stimuli (i.e., letters or words), activity peaks have been observed in left ventrolateral prefrontal regions during n -back task performance, whereas for non-linguistic stimuli (i.e., faces or shapes) activations have been most pronounced in the right dorsolateral prefrontal, lateral premotor and posterior parietal cortex (Owen et al., 2005).

1.2 The effects of technology use on executive functions

The ability to process complex information requires allocating and maintaining attention on relevant stimuli, while ignoring irrelevant distractions from the surrounding. This can be a demanding task, especially when confronted with the attention-grabbing and fast-paced virtual environment offered to us by modern digital technology. Despite the influx of sensory information offered by the information technology that surrounds us, we need to be able to focus our attention on relevant targets, divide our attention between tasks, ignore distractions and flexibly and rapidly move our attention elsewhere when needed while maintaining information in

working memory. How might this overly stimulating environment brought on by ubiquitous modern technology affect our cognitive abilities? One way to answer this question is to study so-called digital natives, that is, young people who have been immersed in digital technologies from very early in their lives (Prensky, 2001). Since these digital natives have, by definition, been subjected from early childhood to a stimulating virtual environment, any effects that technology-mediated activity might have on brain functioning would therefore be especially evident in this generation.

A wide variety of different types of activities involve the use of technology, such as texting or instant messaging, watching videos or movies online, writing or reading blogs, or playing computer games. When it comes to studying how technology-mediated activities affect cognitive abilities, two types of activities in particular have gained extensive research interest. The first is a phenomenon referred to as media multitasking (i.e., the act of using several different media simultaneously), which has been linked to both improvements (e.g., Yap & Lim, 2013) and decrements in attentional abilities (Cardoso-Leite et al., 2015). The second is computer gaming, which in turn has been suggested to improve attention and working memory functioning (e.g., Anguera & Gazzaley, 2015), although there is also contradictory evidence (Bailey et al., 2010; Powers et al., 2013).

1.2.1 Media multitasking and attention

Media multitasking is an activity that refers to using multiple media forms simultaneously, such as instant messaging a friend while watching a YouTube video, or listening to music while reading an online article. The generation of digital natives has been shown to indulge in more multitasking behavior than older generations (Carrier et al., 2009; Zhang et al., 2015), so that almost a third of the time young people use media they use two or more media simultaneously (Rideout et al., 2010). Both positive and negative effects of media multitasking on cognitive functioning have been reported. For example, Yap and Lim (2013) concluded in their study that prolonged simultaneous media usage might reduce the effort needed to maintain split attention. Further, Alzahabi and Becker (2013) reported media multitasking to be linked to improved task switching abilities. It has also been argued that media multitasking might in a sense “train the brain” of digital natives to become more skilled at multitasking. This is because studies have shown that training can induce benefits in multitasking (Lussier et al., 2012; Strobach et al., 2012), especially when the brain’s attention networks are still developing (Rothbart & Posner, 2015).

A less optimistic point of view is that a tendency to multitask can be seen as a result of poor executive control abilities (Loh & Kanai, 2015). Results from several studies support this notion by showing that excessive media multitasking is related to decrements in attentional processes. For example, Ophir and colleagues (2009) found frequent media multitasking to

be associated with an increase in distractibility and greater task switching costs. Further, Sanbonmatsu and colleagues (2013) showed that media multitaskers exhibit declined performance on actual tests of multitasking. Daily multitasking behavior has also been positively correlated with higher self-reported impulsivity (Yang & Zhu, 2015; Uncapher et al., 2015), suggesting that decreased executive control may lead to a tendency to multitask in everyday life while using technology, or vice versa. Media multitasking has also been shown to be associated with a decrease in grey matter volume in frontal regions (Loh & Kanai, 2014) belonging to the executive attention network (Bush et al., 2000). This suggests that media multitasking might have a negative impact on brain areas involved in attentional control. It is important to note, however, that an extensive follow-up study by a separate research group (Minear et al., 2013) failed to replicate the results obtained Ophir and colleagues (2009), and that a recent study failed to find evidence for a relationship between media multitasking activity and distractibility (Ralph et al., 2015).

1.2.2 Gaming and executive functions

Gamers are frequently immersed in a virtual environment that is cognitively demanding, since this environment requires the player to simultaneously and rapidly process information while attending to relevant objects and ignoring irrelevant information (Green & Bavelier, 2006). As a result, commercial computer games may act as cognitive enhancement tools, even though that is not their primary purpose (Anguera & Gazzaley, 2015). According to several studies, expert video game players outperform less experienced game players in a variety of tests tapping visuospatial and attentional processing, e.g. visual selective attention and the spatial distribution of visuospatial attention (Green & Bavelier, 2003), as well as multiple object tracking (Trick et al., 2005). Several recent studies have also found game players to perform well in tests requiring visual task switching (Colzato et al., 2010; Karle et al., 2010). In the domain of working memory, gaming has been linked to improved performance in standard working memory tasks both in terms of reaction times (McDermott et al., 2014) and performance accuracy (Colzato et al., 2013). Similar results have been obtained using different types of working memory paradigms (Boot et al., 2008) using both stationary and dynamic stimuli (Sungur & Boduroglu, 2012), and irrespective of stimulus complexity or time allotted to memory encoding (Blacker & Curby, 2013). It has been suggested that the cognitive benefits of gaming depend on the specific characteristics of different game genres (Oei & Patterson, 2013) so that, for example, only spatially orientated games have the potential to enhance visual cognition (Subrahmanyam & Greenfield, 1994; De Lisi & Wolford, 2002), but this topic remains understudied.

The evidence outlined above suggests that game players may have a benefit in higher-level executive control processes. It is important to note, however, that some studies have found gaming to have negative effects on executive functions (Bailey et al., 2010). Moreover, a recent meta-analysis found negligible associations between gaming and executive functions when only true experiments with a game training paradigm were taken into consideration (Powers et al., 2013). An additional consideration is that the direction of causality between gaming experience and cognitive enhancement is still under debate, since comparing expert gamers to novices tells us nothing about the pre-existing differences in cognitive performance unrelated to gaming between these groups. There are studies, however, showing that cognitive benefits can be obtained by training non-gamers on action video games (Green & Bavelier, 2003) even when the participants have been older adults (Anguera et al., 2013; Belchior et al., 2013). Yet, such training studies have also produced null findings (Boot et al., 2008). It also remains unclear to what extent working memory can be strengthened with directed training. Only highly restrictive transfer has been noted outside of the specific working memory tasks used for training (Eriksson et al., 2015) so that intermediate transfer at most has been noted for young adults (Sandberg et al., 2014).

1.3 Functional magnetic resonance imaging (fMRI)

Brain activity associated with attention and working memory may be localized with fMRI (e.g., Carlson et al., 1998; Hill & Miller, 2010; Janata et al., 2002; Cohen et al., 1997; Martinkauppi et al., 2000). Magnetic resonance imaging (MRI) can be used to construct high-resolution images of different tissue types in the body. An MRI scanner consists of three main components: i) a static magnetic field (expressed in units of Tesla), which aligns the atomic nuclei of the molecule of interest (usually hydrogen); ii) radiofrequency coils consisting of transmitter and receiver coils which produce and receive pulses of electromagnetic fields at the resonant frequency of the atom of interest; and iii) gradient coils, which create a magnetic field that increases in strength along a spatial direction (Huettel et al., 2004). The raw magnetic resonance (MR) signal is created by first placing the imaged object in the static magnetic field, tipping the magnetization of the atomic nuclei away from the static magnetic field axis by applying a radio frequency field, and then measuring the amount of energy emitted by the nuclei as they return to their equilibrium after the pulse ends. The function of the gradient coils is to add spatial information into the raw MR signal with another gradient magnetic field.

Depending on what aspect the object of interest one wants to measure, different MR pulse sequences can be used. They detect different types of signal after the pulse produced by the radiofrequency coils is turned off and nuclei return to equilibrium. For example, measuring contrast between tissue

types is achieved by using a T1-weighted sequence. The T1 signal indicates the amount of time for the nuclei of interest to return to their equilibrium state, and this time is different for protons in different tissue types, such as grey and white matter (Bottomley et al., 1984).

fMRI does not discern between different tissue types like structural MRI, but it utilizes a different type of imaging sequence sensitive to the difference between active and non-active tissue. It can be used to measure changes in blood volume and flow, which are indirectly correlated with neuronal activity (Logothetis, 2003). As the neuronal activity of a brain region increases, so does the flow of oxygenated blood to that region, as neurons need the glucose and oxygen delivered by blood to fuel the upsurge of neural transmission. The basis of fMRI is the blood-oxygen-level-dependent (BOLD) signal that is sensitive to the change in the amount of deoxygenated hemoglobin (Ogawa et al., 1990). When hemoglobin is deoxygenated, it is paramagnetic and its magnetic susceptibility (i.e., the intensity of magnetization of a substance when placed in a magnetic field) is greater than when it is oxygenated, which causes a greater local distortion in the static magnetic field of the MRI scanner. This distortion, in turn, causes the nuclei to lose magnetization faster via the T_2^* decay, which depends on the time constant T_2^* . MR pulse sequences such as echo-planar imaging (EPI) that are sensitive to T_2^* show more MR signal when blood is highly oxygenated than when it is deoxygenated. In other words, the deoxygenation of blood decreases its visibility in T_2^* -weighted images, meaning that the BOLD signal is detected because oxygenated hemoglobin displaces deoxygenated hemoglobin that had been interfering with or suppressing the MR signal (Huettel et al., 2004).

2 AIMS OF THE PRESENT THESIS

The aim of the present thesis was to investigate the functional brain networks related to attention and working memory processes, and to examine whether technology-mediated activities in adolescents and young adults are associated with changes in these cognitive functions or their accompanying neural activity. Of the three studies included in the thesis, two addressed brain activity related to selective and divided attention (**Study I** and **Study II**), and one explored the activity in cortical networks recruited by auditory and visual working memory (**Study III**). **Study I** included only adult participants performing a task demanding selective or divided attention. **Studies II** and **III** included adolescent and young adult participants who performed this attention task (**Study II**) and a working memory task (**Study III**).

Study I aimed at examining whether any additional cortical structures are recruited when two tasks are performed simultaneously in comparison with when those same tasks are performed separately. To this end, fMRI was measured as participants performed a sentence evaluation task involving either only spoken or written sentences, or both sentences simultaneously. We expected to see increased activity in semantic processing areas when the participants were required to perform the reading and listening tasks simultaneously. We hypothesized that this increase would be non-additive because of limited processing capacity, leading to deficits in performing two simultaneous sentence evaluation tasks.

Study II aimed at elucidating whether daily media multitasking activity is associated with attentional functioning or task-related brain activity in adolescents and young adults. This was accomplished by using the experimental design of **Study I** and examining correlations between daily self-reported media multitasking activity, brain activity and performance during the sentence evaluation task. We expected media multitasking to be associated with increased distractibility, but not with benefits in multitasking performance.

Study III examined the relationship between self-reported gaming experience, performance and brain activity in task-related brain regions during a working memory task in adolescents and young adults. In this study, fMRI was measured as participants performed an auditory-visual *n*-back task, where the modality of the presented stimuli (spoken and written vowels) switched at unpredictable intervals. We expected to see that participants with more gaming experience would exhibit better working memory performance and smaller modality switching costs.

3 METHODS

3.1 Participants

An informed written consent was obtained from all participants (and from a guardian in the case of underage participants) in **Studies I-III** before the experiment, and they received monetary compensation for their participation. All participants were right handed and native Finnish speakers with normal hearing, normal or corrected-to-normal vision, and no self-reported history of psychiatric or neurological illnesses. The experimental protocol for **Study I** was approved by the Coordinating Ethics Committee of The Hospital District of Helsinki and Uusimaa, Finland. The experimental protocol for **Study II** and **Study III** was approved by the Ethics Committee for Gynaecology and Obstetrics, Pediatrics and Psychiatry of The Hospital District of Helsinki and Uusimaa, Finland.

Details of the participants in each study are reported in Table 1. The participants in **Study II** were a subset of the participants used in **Study III**, as all of the participants in **Study III** did not fill out an additional questionnaire mailed to the participants afterwards, which was crucial to the analyses of **Study II**.

Table 1. The number, age range and gender ratio of participants included in **Studies I- III**

	N	Age range	Male/Female ratio
Study I	18	21-34	9/9
Study II	149	13-24	73/76
Study III	167	13-24	80/87

In **Study I**, all participants were adult volunteers. In **Study II** and **Study III**, the volunteering participants belonged to three different age cohorts: 13- and 16-year-old pupils and 20–24-year-old university students. These participants were selected from a large sample (n=2977) of respondents who filled out a questionnaire asking them about their use of digital technologies in everyday life. This questionnaire data had been gathered as a part of the research project titled Mind the Gap between Digital Natives and Educational Practices. The questionnaire included a Sociodigital Participation (SDP) inventory (Hietajärvi et al., 2015) assessing various dimensions of technology-mediated practices in everyday life. Using a latent profile analysis (Vermunt & Magidson, 2002) the participants (each cohort separately) were grouped into three profiles representing their SDP practices: basic participators who demonstrated the least technology-mediated activity, gaming-oriented participators who focused especially on action and social gaming as separated from recreational gaming, and creative

participants characterized by intensive engagement in socio-digital activities in general and creative use of knowledge and media in particular. These profiles were not used in any subsequent analyses as all participants demonstrated some level of gaming or socio-digital activity, but were only used to sample participants. Respondents who were ineligible for an fMRI measurement or respondents with any learning difficulties or notably poor school performance were not contacted.

3.2 Variables related to technology use (Study II and III)

Three variables describing the daily technology-mediated activities of the participants in **Study II** and **Study III** were formed based on the SDP inventory: i) Media multitasking (MMT) Score; ii) Gaming Score; and iii) Digital activity (DA) Score. The MMT Score reflected the amount of time each participant reported spending using several media simultaneously (e.g., watching YouTube videos while instant messaging with a friend). The Gaming Score was used as an indicator of how often participants reported playing 10 different genres of computer and video games. Three latent gaming variables were also extracted from the scale used to calculate the Gaming Score: i) Serious Games (i.e., role playing games, adventure games, strategic games, and shooter games), ii) Fun Games (i.e., music games, exercise games, party games and puzzle games), and iii) Sports games (i.e., sports games and racing games). The DA Score reflected the amount of overall daily digitally mediated activity (e.g., talking on the phone or sending e-mails) of the participants, and it was used as a control variable when analyzing results related to the MMT Score or Gaming Score.

3.3 Stimuli (Study I and II)

In **Study I** and **Study II**, participants performed a sentence evaluation task involving sentences presented in the visual or auditory modality, or both. In the visual modality, the sentences in **Study I** were either written sentences or sentence-like nonsense text. The written sentences were either semantically congruent or incongruent sentences in Finnish. The incongruent sentences were created by taking a subset of the congruent sentences (e.g., “This morning I ate a bowl of cereal”) and replacing the last word of each of these sentences with a semantically incongruent (but syntactically plausible) word (e.g., “This morning I ate a bowl of shoes”). The nonsense text was created by randomly selecting a subset of the congruent written sentences, replacing each vowel in those sentences with a different vowel, and ensuring that the resulting sentences consisted of only non-words. In **Study II**, the real sentences were otherwise identical to those in **Study I**, except that the last word of the sentence was replaced by a row of letters *x* (as many letters *x* as there were letters in the last word) for the first 2 s of a trial after which the last word was displayed instead of the letters *x*. The conditions with nonsense text were not included in the analyses of **Study II**. In both studies, the written sentences were projected onto a

mirror mounted on the head coil and presented in the middle of the screen (font: Arial, size 14). The size of the sentences at the viewing distance of ~40 cm was ~1.4° vertically and ~24° horizontally.

In the auditory modality, the stimuli used in **Study I** consisted of speech, nonsense speech, and music. The spoken sentences were semantically congruent or incongruent Finnish sentences spoken by a female native Finnish speaker. The incongruent sentences were created by replacing the last word in the congruent sentences with a semantically incongruent word. The nonsense speech stimuli were nonsensical sentences (created the same way as the nonsense written text described above) spoken by a female native Finnish speaker. The music stimuli were 2.5 s excerpts of instrumental music, so that various genres from hip-hop to classical music were represented in order to minimize effects of the participants' personal musical preferences. Music was chosen as an additional distractor due to its ecological validity as a distractor, and also because effects of background music on cognitive performance has been a topic of interest in several other studies (e.g., Furnham & Bradley, 1997). In **Study II**, the auditory stimuli were identical to those in **Study I**, but the conditions with nonsense speech were not included in the analyses. The auditory stimuli in both studies were presented binaurally through insert earphones (Sensimetrics model S14; Sensimetrics, Malden, MA, USA). All auditory stimuli were broadband filtered (high-pass cut-off at 100 Hz and low-pass a cut-off at 7000 Hz). The intensity of auditory stimuli was scaled so that their total power in RMS units was similar (0.1). The intensity of the sounds was ~80 dB SPL as measured from the tip of insert earphones.

In **Study I**, auditory and visual functional localizers were used in order to accurately localize the respective sensory cortices of each subject. The auditory functional localizer was created by phase-scrambling spoken sentences. The visual functional localizer was a contrast-reversing checkerboard flickering at 8 Hz. The size of the checkerboard was similar to written sentences (~1.4° × ~24°), and it was centered at the middle of the screen. The auditory and visual localizers were presented simultaneously for the same duration as the sentences, followed by a 1-s fixation cross (~1.4° × ~1.4°) at the center of screen.

3.4 Stimuli (Study III)

In **Study III**, participants performed an auditory-visual *n*-back task with vowels. In the visual modality, the stimuli were the Finnish vowels *a*, *e*, *u* and *y*, which were presented in the middle of the screen. The vowels were presented in four different fonts, so that the font of each vowel was assigned randomly, but if the vowel in the 1- or 2-back condition matched a vowel presented 1 or 2 trials back, respectively, it was never written in the same font as the vowel preceding it by *n* trials. The size of the vowels was ~1.4° horizontally and vertically. Each vowel was surrounded by a square (~2.9° horizontally and vertically) with a fixation point in the center, both of which were on the screen throughout the entire block. The visual stimuli were projected onto a mirror mounted on the head coil. In the auditory modality,

the stimuli were Finnish vowels (/a/, /e/, /u/ and /y/) spoken by four different native Finnish speakers (2 males, 2 females). The voice speaking the vowel was assigned randomly, but if the vowel in the 1- or 2-back condition matched a spoken vowel presented 1 or 2 trials back, respectively, it was never spoken by the same person as the *n*-back vowel. The spoken vowels were presented through insert earphones (Sensimetrics model S14; Sensimetrics, Malden, MA, USA) binaurally. All spoken vowels were broadband filtered (high-pass cut-off at 100 Hz and low-pass a cut-off at 7000 Hz). The intensity of the spoken vowels was adjusted so that their total power in RMS units was similar (0.1). The intensity of the spoken vowels was ~80 dB SPL as measured from the tip of the earphones

3.5 Details of the experimental design (Study I and II)

In **Study I**, a total of nine different experimental conditions were used. In the two *unimodal conditions* participants were instructed to attend to the sentences in just the visual modality (1) or auditory modality (2), while no stimuli presented in the other modality. In the four *selective attention conditions*, participants were asked to ignore distractor stimuli that were presented in the other modality, so that the auditory distractors were spoken sentences (3), music (4) or nonsense speech (5), and the visual distractors were written sentences (6). In the *divided attention condition* (7), the participants were presented with simultaneous spoken and written sentences and instructed to attend to both modalities simultaneously. Two additional visual distractor conditions were included in order to control for eye movements. In these two conditions, a moving fixation cross was present on the screen and the participants were instructed to follow it while attending to speech (8), or nonsense written sentences were presented on the screen and the participants were instructed to scan through the nonsense text while attending to speech (9). In **Study II**, only six conditions were included in the study: the two unimodal conditions, the selective attention conditions with speech, text or music distractors, and the divided attention condition (i.e., conditions 1-4 and 6-7 in **Study I**). The other three conditions were left out from Study II in order to simplify the study design, and because they were found to provide no additional relevant information in the fMRI analyses of **Study I**. The unimodal conditions were included so that baseline task-related activity without distractors could be established if needed and compared with the distracted attention condition. The selective attention conditions were necessary to include in the study, as investigating distractibility was one of its main aims. The condition with music as a distractor was included in order to examine effects of non-linguistic distractors and to see whether these effects on behavior or brain activity might differ from those elicited by linguistic distractors. Finally, the divided attention condition was included in order to determine whether media multitasking might be linked to better dual tasking ability. A schematic

illustration of the six task conditions that were included in the analyses of both **Study I** and **Study II** is provided in Figure 1.

In the beginning of each block (corresponding to each of the task conditions), instructions for the current task type were shown for 3.5 s. In subsequent task blocks, sentences (visual or auditory) or sentence pairs (visual and auditory) were presented for a duration of 2.5 s. Each sentence was followed by a 1 s response window during which the participants were instructed to respond with an appropriate button press whether the attended sentence was congruent or not using their right index and middle finger, respectively. In the divided attention condition, participants were asked to decide whether or not both sentences were congruent (both sentences were never incongruent). During the response window, a question mark was presented at the center of screen (size $1.4^\circ \times 1.0^\circ$). In **Study I**, a fixation cross preceded each written sentence for 500 ms where the first letter of the sentence subsequently appeared. In **Study II**, the fixation cross was always at the center of the screen. When only speech stimuli were presented, only a fixation cross was present at the center of screen. At the end of each block, the participant was shown the percentage of correct responses in that block for 2 s.

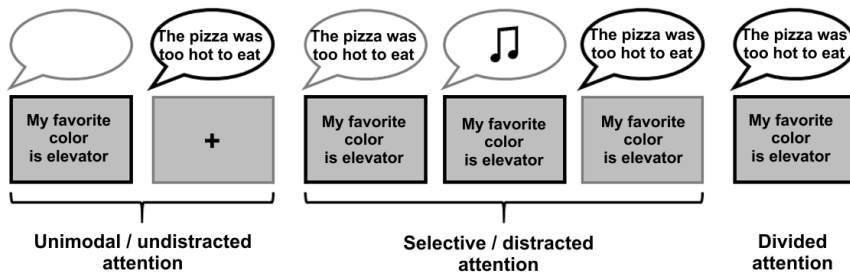


Figure 1. *A schematic illustration of the task conditions included in the analyses of both **Study I** and **Study II**. The thicker black outlines denote which modality/modalities participants were instructed to attend to. In the actual experiment, each sentence was presented only once to each participant.*

There were four functional runs in **Study I**, and three functional runs in **Study II**. Each run included one block of each task type, except the divided attention task was repeated twice. Each block included 12 trials (i.e., sentences, sentence pairs, or functional localizers). This resulted in a total of 96 trials in **Study I** and 72 trials **Study II** for the divided attention task, and 48 trials in **Study I** and 36 trials in **Study II** for all the other task types. The order of tasks within the run was random, except that the rest block was always between the 6th and 7th task block. The presentation of sentences was randomized in the following way. First, the sentences were divided randomly into as many sets as there were runs, with these sets being identical for all

participants. Then the order of sentences within a set was randomized, and the presentation order of these sets was randomized and counterbalanced across participants. The congruent and incongruent versions of the same sentence were never presented within the same run, and each sentence was presented only once to each participant. In addition to the task blocks, a block of rest (where only a fixation cross was present on the screen) and a block for the combined auditory and visual functional localizers was included in **Study I**.

3.6 Details of the experimental design (Study III)

In **Study III**, participants performed three levels of the n -back task: 0-, 1- and 2-back. The experimental setup for the n -back task is depicted in Figure 2. In the beginning of each block (corresponding to one level of the n -back task), instructions for the current task level were shown for 6 s. Then, 32 vowels (visual or auditory) were presented, each with a duration of 500 ms. The modality of the presented vowel was switched randomly on every 3rd, 4th, 5th or 7th vowel, resulting in seven modality switches in a block. This was done so that participants were not able to anticipate a modality switch. Each vowel was then followed by a 2500 ms retention period during which the participants were instructed to respond. In the 0-back condition, this meant responding with a right index finger or middle finger button press whether the presented vowel had been presented in the visual or auditory modality, respectively. In the 1-back and 2-back conditions, this meant responding with an appropriate button press on each trial whether the vowel did or did not match the vowel presented n trials back (irrespective of whether the preceding vowel n trials back was a written or a spoken one) using their right index or middle finger, respectively. There were 10 match trials in each block of 32 trials. When auditory stimuli were presented, the square surrounding the vowels and the fixation point remained on the screen. At the end of each block, the participant was shown the percentage of correct responses in that block for 3 s.

There were two functional runs, 3 blocks (corresponding to the three n -back task levels presented in random order) in each run, and 32 vowels in each block. This resulted in a total of 64 trials for each n -back task level. Before beginning the n -back task, the participants had performed the sentence evaluation task used for **Study II**, and had therefore already spent around 30 minutes in the scanner.

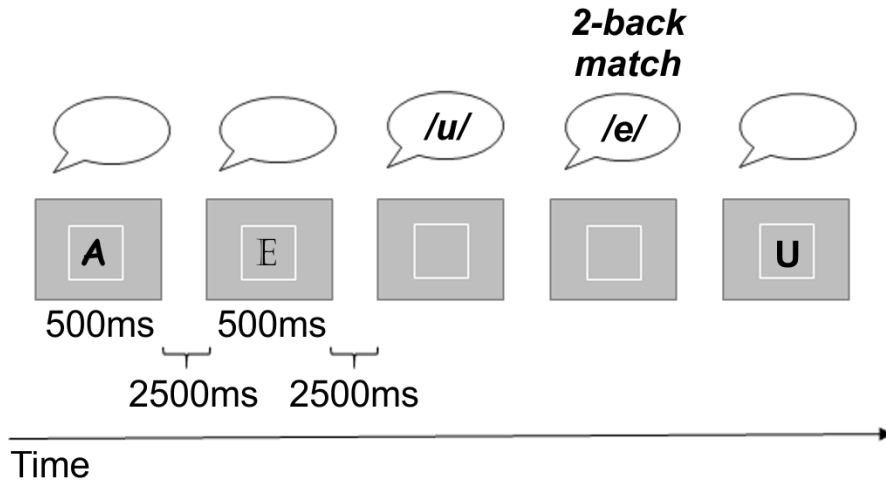


Figure 2. *A schematic illustration of the n-back task showing five trials of the 2-back condition including one vowel matching with a vowel delivered 2 trials back.*

3.7 Analysis of behavioral data

In **Study I**, analyses of performance accuracy were conducted in order to study general task-related effects. To this end, repeated measures analyses of variance (ANOVAs) were used to compare performance between i) the three task levels (unimodal conditions vs. selective attention conditions vs. divided attention condition), ii) the three conditions with different auditory distractor types (attention to text with a speech, nonsense speech or music distractor) and the three conditions with different visual distractor types (attention to speech with a text vs. nonsense text vs. moving fixation cross distractor), and iii) conditions based on the attended modality (conditions where attention was targeted to written sentences vs. speech sentences vs. both written and speech sentences). In **Study II**, the main interest was to study the relationship between the MMT Score and performance while controlling for relevant background variables, so the percentage of correct responses were subjected to analyses of covariance (ANCOVA) with the participant's gender and age (defined as Age Cohort) as the fixed factors, and MMT Score and DA Score as the covariates. In this way, the association between MMT Score and performance in the three task types (undistracted conditions vs. distracted conditions vs. divided attention condition) as well as between the three different distractor types (text vs. speech vs. music) was studied. The divided attention condition was also studied more carefully by conducting additional ANCOVAs where the percentage of correct responses was calculated based only on the first three divided attention blocks, and where run number was added as an additional within-subjects factor. Partial

correlation coefficients were also calculated per task type between the percentage of correct responses and the MMT Score while controlling for Age Cohort and Gender. In **Study III**, general task-related effects were first examined by conducting a repeated-measures ANOVA so that the effects of Memory Load (0-back vs. 1-back vs. 2-back) and Modality Switch (switch vs. no switch) could be discerned. The association between Gaming Score and performance was then studied by conducting repeated measures ANOVAs where Memory Load (using both absolute values: 0-back vs. 1-back vs. 2-back, as well as relative values: 1-back vs. 0-back, 2-back vs. 0-back and 2-back vs. 1-back) and Modality Switch were included as within-subjects variables, Gender and Age Cohort as between-subjects factors, and Gaming Score, DA Score and the participant's grade point average (GPA) as covariates. Partial correlation coefficients were also calculated between Gaming Score and performance while controlling for Gender, age, DA Score and GPA. The same ANOVA was also conducted separately for switch trials and for non-switch trials. In addition, a repeated-measures ANOVA was conducted where modality (visual vs. auditory) was included as a within-subjects variable, as well as an ANOVA with run number as a within-subjects variable. For those analyses producing significant main effects or interactions involving Gaming Score, the analyses were repeated so that Gaming Score was replaced as the between-subjects variable by the three latent gaming variable scores. For the *n*-back task in **Study III**, indices related to response speed could also be calculated, since there was no fixed response window in this task type. All of the statistical analyses conducted for the percentage of correct responses were therefore also conducted for response times.

For all conducted ANOVAs the Greenhouse-Geisser p-value was used (as indicated by the correction value ϵ) if the Mauchly's test of sphericity showed a significant result. When the ANOVA yielded a significant result, Bonferroni post hoc tests were conducted. IBM SPSS Statistics 21 for Windows (IBM SPSS, Armonk, NY, USA) was used for statistical analyses.

3.8 MRI/fMRI data acquisition and analysis

MRI/fMRI data acquisition was identical for **Studies I-III**. The imaging was carried out with a 3 T MAGNETOM Skyra whole-body scanner (Siemens Healthcare, Erlangen, Germany) with a 20-channel head coil. The functional echo planar (EPI) images were acquired with an imaging area consisting of 43 contiguous oblique axial slices using the following parameters: TR 2500 ms, TE 32 ms, flip angle 75°, voxel matrix 64 x 64, field of view 20 cm, slice thickness 3.0 mm, in-plane resolution 3.1 mm x 3.1 mm x 3.0 mm. Image acquisition was performed at a constant rate, but it was asynchronized with stimulus onsets. High-resolution anatomical images were acquired from the participants using a 256 x 256 voxel matrix and an in-plane resolution of 1 mm x 1 mm x 1 mm

The preprocessing and statistical analysis of fMRI data for **Studies I-III** was performed using the Statistical Parametric Mapping (SPM8/SPM12) analysis package (Wellcome Department of Cognitive Neurology, London, UK; Friston et al., 1994). During pre-processing, the slice timing was corrected, data were motion corrected, high-pass filtered (cut-off at 1/128 Hz), and spatially smoothed (6 mm Gaussian kernel). The EPI images were intra-individually realigned to the middle image in each time series and unwarping was performed. Then the anatomical images were normalized to a canonical T1 template (MNI standard space) provided by SPM, and the transformations were then used as a template to normalize the functional volumes for each participant with the following parameters: tri-linear interpolation, 3 mm x 3 mm x 3 mm using 16 nonlinear iterations.

Region-of interest (ROI) analyses were conducted in order to study signal changes within task-relevant cortical regions. The ROIs were devised by first plotting the whole-head contrast of interest on an inflated surface, and then manually drawing the ROIs using Freesurfer software to cover the regions showing statistically significant activity for that contrast. In **Study I**, *Dual-tasking ROIs* were created by contrasting the divided attention separately with the selective attention to text condition and the selective attention to speech conditions. These ROIs were created in order to study how task difficulty was reflected in activity of brain regions crucially involved in dual tasking. In addition, *Semantic ROIs* were created by contrasting all incongruent sentences vs. congruent sentences within each modality. These ROIs were used to target analyses to regions involved in evaluating the semantic content of language, since both component tasks were linguistic in nature. Contrasting incongruent with congruent sentences or stimuli has been used in several previous studies in order to map out brain areas related to semantic evaluation (e.g., Kuperberg et al., 2003). The visual and auditory cortices were also used as ROIs, and they were defined as voxels significantly activated by the functional localizers. These ROIs were used to investigate whether competition at the level of the sensory cortices contribute to multitasking limitations. In **Study II**, cortical regions showing activity modulations that correlated with the MMT Score were subjected to ROI analyses in order to further elucidate the role of these regions in task processing. A ROI analysis was also conducted for the right and left superior parietal lobule (SPL; Brodmann area 7), localized by using the Destrieux atlas (Destrieux et al., 2010), since this area is known to be involved in covert and overt shifts of attention (Corbetta et al., 1998) and attentional capture by distractor stimuli (de Fockert et al., 2004). In **Study III**, ROIs were defined as the regions showing greater activity during a combination of activity during 1- and 2-back than during 0-back in the whole-head analysis.

In all ROI analyses, the mean BOLD signal changes were calculated in each ROI and then subjected to ANOVAs that included the variables of interest and any possible control variables. In the case of **Study I**, this meant that ANOVAs for activity within the *Dual-tasking ROIs* and sensory cortex

ROIs were conducted in order to compare: i) all nine task conditions, ii) the three task types (unimodal conditions vs. selective attention conditions vs. divided attention condition), iii) interactions between the three task levels and the hemisphere of the ROI, and iv) the attended modality of the condition (visual vs. auditory). For the *Semantic ROIs*, an ANOVA comparing the three task types, the hemisphere of the ROI and the semantic congruence of the sentence was conducted. In **Study II**, task-related effects were studied by conducting an ANOVA for each of the ROIs, which compared undistracted to divided attention while controlling for Gender and Age Cohort. Partial correlations (controlling for Gender and Age Cohort) were then calculated between MMT Score and activity during distracted attention in each of the ROIs. This correlation was also calculated using the MMI instead of the MMT Score. Finally, partial correlation coefficients (controlling for Gender and Age Cohort) were calculated between activity within the ROIs and task performance during the different task types. In **Study III**, repeated measures ANOVAs were conducted in order to study the association between activity in the ROIs during the different Memory Loads (1-back vs. 0-back, 2-back vs. 0-back and 2-back vs. 1-back) and Gaming Score, while controlling for Gender, Age Cohort, DA Score and GPA. These ANOVAs were also conducted separately for switch and non-switch trials. Activity during non-switch trials was further studied by including the modality of the vowel (visual vs. auditory) as a within-subjects variable. The three latent gaming variables were not included in these analyses due to the fact that they had no significant effects on any of the key performance measures. Because the aim of the current study was specifically to examine how cognitive benefits related to gaming are reflected in cortical activity, including the latent gaming variables in the analysis of brain activity was therefore not justified. Partial correlations (controlling for Gender, Age Cohort, DA Score and GPA) were calculated between task performance and activity in the ROIs. Mediation analysis was used to examine possible mediating effects of performance accuracy on the relationship between Gaming Score and activity in the ROIs.

In **Study II** and **Study III**, cortical thickness within each ROI was analyzed using Freesurfer's automatic processing stream for volume and thickness estimates (Reuter et al., 2012). The grey matter volume estimates of the ROIs were then subjected to ANOVAs in order to make sure that any differences in ROI activity related to the variables of interest (i.e. MMT Score and Gaming Score) were not due to differences in cortical thickness.

4 RESULTS AND DISCUSSION

4.1 Cortical networks recruited by selective and divided attention (Study I)

In **Study I**, we compared brain activity changes due to selective and divided attention during sentence evaluation tasks. Firstly, we found that divided attention lead to significant performance decrements when compared with the unimodal and selective attention conditions. Performance was also significantly worse during the selective than the unimodal attention condition. When fMRI data was analyzed, divided attention was found to not recruit any additional cortical structures when compared with selective attention, but resulted in increased activity in medial and lateral frontal regions which were also activated by the component tasks when performed separately (yellow areas in Figure 3A). Divided attention was associated with significantly enhanced activity in lateral and medial prefrontal cortical regions in relation to either selective attention to text or selective attention to speech (yellow areas in Figure 3B).

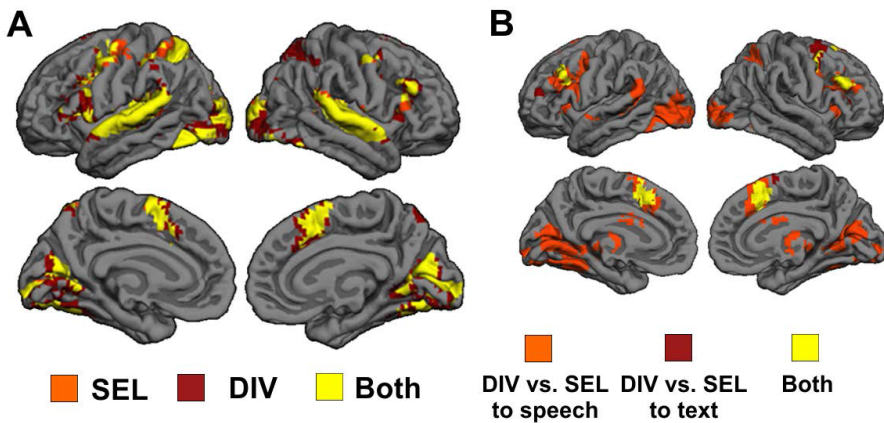


Figure 3. (A) Significant activity enhancements during the selective (SEL) and divided attention (DIV) conditions in relation to rest. Cortical regions showing enhanced activity during selective attention (orange) and divided attention (red) showed a significant degree of overlap (yellow). Voxel-wise height threshold $t=4.7$, cluster size >250 , cluster corrected $p < 0.001$. (B) Significant activity enhancements during divided attention in relation to selective attention to text with a speech distractor (red) and selective attention to speech with a text distractor (orange) both activated medial and lateral frontal regions (yellow). Voxel-wise height threshold $t=2.5$, cluster size >250 , cluster corrected $p < 0.001$.

ROI analyses for activity in these regions (*Dual-tasking ROIs*) revealed a gradual activity increase related to task difficulty (unimodal condition < selective attention < divided attention). When both task performance and ROI activity for each of the nine experimental task conditions was examined, a pattern was observed where increased task difficulty was coupled with worse performance and increased ROI activity (Figure 4). The visual cortex was found to be activated to the same extent during divided attention as during attention to visual stimuli in both the unimodal and selective attention conditions, and an analogous pattern of results was observed for the auditory cortex. ROI analyses of cortical regions related to semantic processing (*Semantic ROIs*; yellow areas in Figure 5A) revealed that activity in these regions increased significantly during divided attention compared with the unimodal and selective attention conditions (Figure 5B).

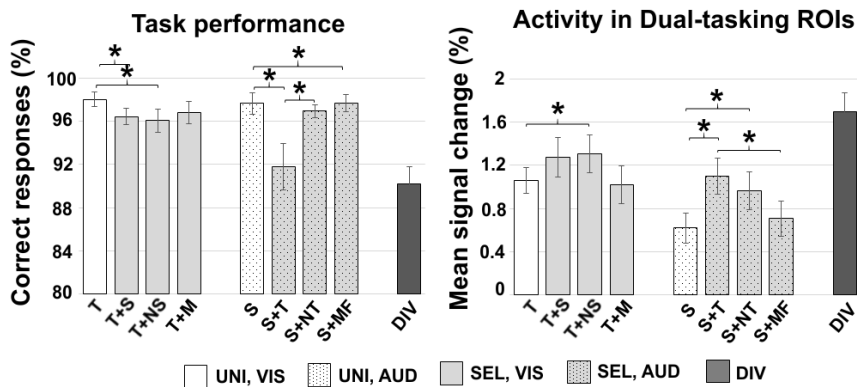


Figure 4. Task performance and activity in the Dual-tasking ROIs during the nine experimental task conditions revealed a pattern where increased task difficulty was coupled with worse performance and increased ROI activity. The mean signal changes are averaged across all five Dual-tasking ROIs. Error bars indicate SEMs. Conditions differing significantly ($p < 0.05$) from each other are indicated with asterisks. (UNI = unimodal conditions, SEL = selective attention conditions, DIV = divided attention condition, VIS = attention directed to visual modality, AUD = attention directed to auditory modality, T = attention to text in a unimodal condition, T+S = attention to text with a speech distractor, T+NS = attention to text with a nonsense speech distractor, T+M = attention to text with a music distractor, S = attention to speech in a unimodal condition, S+T = attention to speech with a text distractor, S+NT = attention to speech with a nonsense text distractor, S+MF = attention to speech with a moving fixation cross distractor).

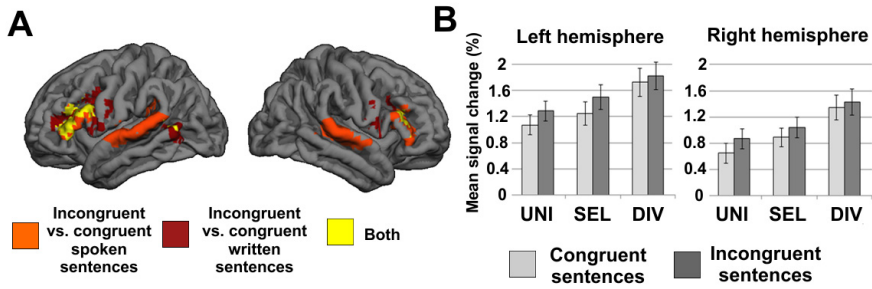


Figure 5. (A) Brain areas showing significant activity enhancements for attended incongruent written (red) and spoken (orange) sentences in relation to respective congruent sentences overlapped in the inferior frontal gyri (yellow). Voxel-wise height threshold $T=2.5$, cluster size > 250 , cluster-level Familywise error corrected $p < 0.001$. (B) Mean signal changes (%) in the Semantic ROIs for attended incongruent and congruent sentences compared with rest during the unimodal (UNI), selective attention (SEL) and divided attention (DIV) conditions in the left and right hemisphere demonstrated a graded activation increase related to task difficulty. Error bars indicate SEMs.

Our results therefore provide more support for the claim (e.g., Adcock et al., 2000; Bunge et al., 2000) that dual-tasking does not recruit new cortical areas apart from those activated by the component tasks. Conversely, our results did not provide support for the notion that crossmodal inhibition of the sensory cortices contribute to performance decrements during audiovisual multitasking, as has previously been suggested (Loose et al., 2003; Johnson & Zatorre, 2005). A more likely bottleneck during multitasking was found in regions related to language processing, as both component tasks used in our study required the participants to make sentence congruency judgments. More specifically, when brain regions involved in semantic processing were specifically examined, an increase in activity during divided attention was observed in these regions when compared with the unimodal and selective attention conditions. This suggests that when two semantic tasks were performed in parallel, performance accuracy declined because more demands were placed on semantic processing areas. Taken together, the results from **Study I** suggest that performance decrements during multitasking are due to interference occurring at the level brain regions commonly activated by the component tasks (Roland & Zilles, 1998), and possibly due to a surplus of activation in lateral and medial prefrontal cortical regions during divided attention.

4.2 Associations between media multitasking and attention (Study II)

In **Study II**, we investigated the associations between daily self-reported media multitasking activity of adolescent and young adult participants and task performance and brain activity during a sentence evaluation task which was nearly identical to that used in **Study I**. We found that higher scores on a media multitasking questionnaire were associated with worse performance specifically during distracted attention, when participants were instructed to attend to written or spoken sentences while a distractor stimulus was presented in the unattended modality (Figure 6A). In the divided attention condition, no significant association between media multitasking and performance was observed. Regions in the right lateral and medial prefrontal cortices demonstrated a main effect of media multitasking so that higher levels of media multitasking were associated with increased activity in these regions, but only during the distracted attention condition (Figure 6B). ROI analyses of these prefrontal regions revealed that activity within these regions were significantly higher during divided attention than during undistracted attention (Figure 7).

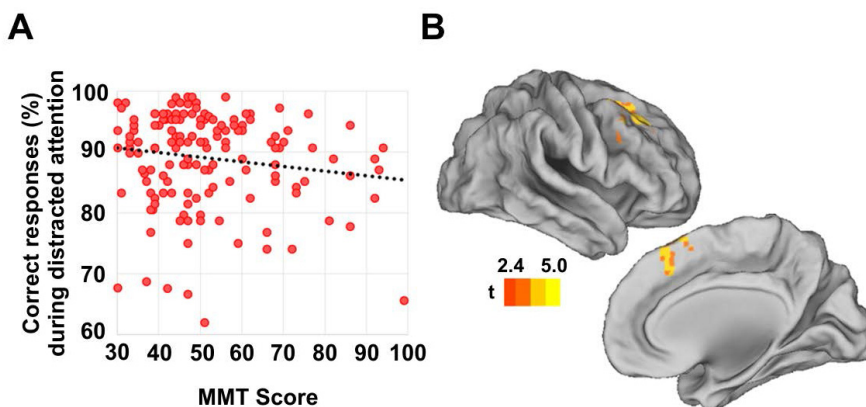


Figure 6. (A) The percentage of correct responses during the distracted attention condition was negatively correlated with the Media Multitasking (MMT) score. A fitted regression line is indicated by a dashed line. (B) Colored areas indicate the prefrontal cortical regions in the right hemisphere showing a significant positive association between the MMT Score and brain activity during the distracted attention condition. Voxel-wise height threshold $t=2.35$, cluster size >150 , cluster corrected $p < 0.005$.

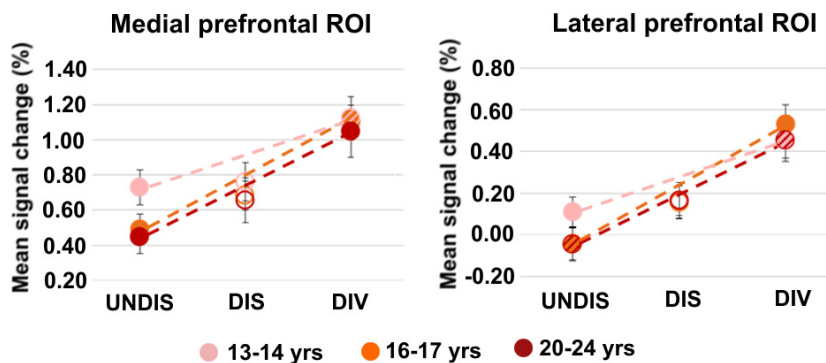


Figure 7. Mean signal changes within the medial and lateral frontal regions was greater during divided attention (DIV) than during undistracted attention (UNDIS) in all three age cohorts. The distracted attention condition (DIS) is included in the two graphs (open circles) for illustrative purposes, but not included in the ANOVAs because this condition was used when selecting the ROI. Overlapping data points are denoted with striped circles. Error bars represent standard errors of the mean.

No association was found between media multitasking and performance in the divided attention condition in the study, a result which has previously been demonstrated by other research groups (Alzahabi & Becker, 2013; Sanbonmatsu et al., 2013). This seemingly counter-intuitive result may be explained by several different factors. Firstly, daily multitasking most likely consists not only of dual-tasking in the classical sense, but of a combination of divided attention, task switching and performing several automatized functions in parallel (Carrier et al., 2015). In addition, a fundamental difference is also likely to exist with multitasking in the laboratory setting and multitasking in real life, as dual tasks used in laboratory experiments often force participants to adopt a more serial mode of task-processing than in everyday life (Fischer & Plessow, 2015). Finally, even if heavy media multitaskers were better than others at performing several tasks simultaneously in real life, this might not be detected in laboratory settings due to the fact that transfer effects in cognitive training studies in general are often quite narrow and specific to the features of the trained task (Green & Bavelier, 2008).

The performance decrements during distracted attention observed in the current study were coupled with increased activity in right prefrontal regions, which are known to be important for attentional control (Garavan et al., 1999; Aron et al., 2003; Fassbender et al., 2006). In addition, activity in these regions were shown to increase incrementally in response to task difficulty. The observed coupling between media multitasking and prefrontal

activity therefore suggests that the distracted attention condition required more effort and executive control from the participants the higher their daily media multitasking level was. In other words, the increase in prefrontal recruitment may reflect an increased need to redirect attention and maintain it on the central task in the presence of to-be-ignored distractors.

4.3 Associations between gaming and working memory (Study III)

In **Study III**, we studied associations between daily self-reported gaming activity, working memory performance and task-related brain activity in adolescents and young adults. We found that gaming activity was correlated with better task performance when comparing the most demanding task level with an easier one, both with regard to the percentage of correct responses (Figure 8A) as well as reaction times in these component tasks. Reaction times were also less affected by a modality switch when comparing 2-back to 1-back in participants with higher Gaming Scores (Figure 8B).

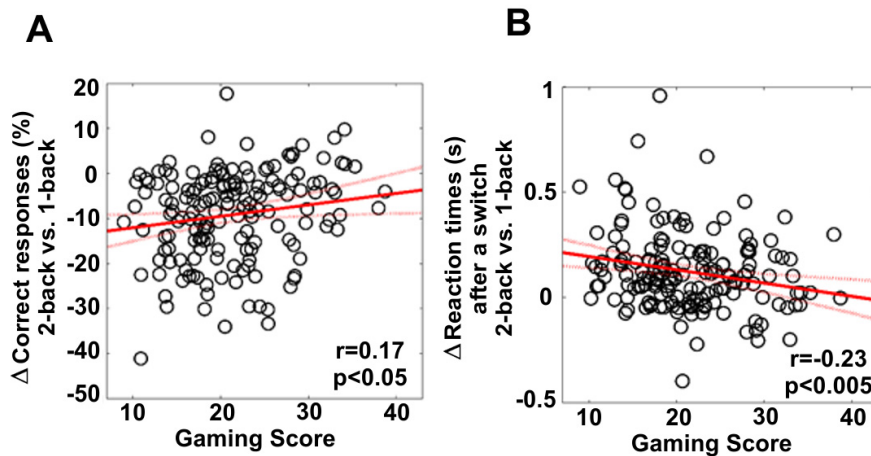


Figure 8. The participants' Gaming Scores were **(A)** positively correlated with the difference in the percentage of correct responses between 2-back and 1-back tasks, and **(B)** negatively correlated with the difference in response times following a modality switch when comparing 2-back and 1-back tasks. The data in all figures are adjusted for Gender and Age Cohort. A fitted regression slope (a bright red line) and 95% confidence interval bounds (light red lines) are shown in both figures.

The type of game genre played was not a significant factor in determining performance, as the latent gaming variables did not reproduce any of the main behavioral findings related to Gaming Score. Further, Age

Cohort did not significantly interact with Gaming Score in any of the behavioral analyses.

Brain activity was studied in regions that were significantly more active during 1- and 2-back than during 0-back (Figure 9A), and a significant association was found between the participant's Gaming Score and activity in the middle frontal gyrus (MFG) ROIs in both hemispheres (Figure 9B). More specifically, the higher the Gaming Score of a participant was, the smaller was the observed change in MFG activity from 0-back to 1-back, but the greater was the observed change in MFG activity from 1- back to 2-back.

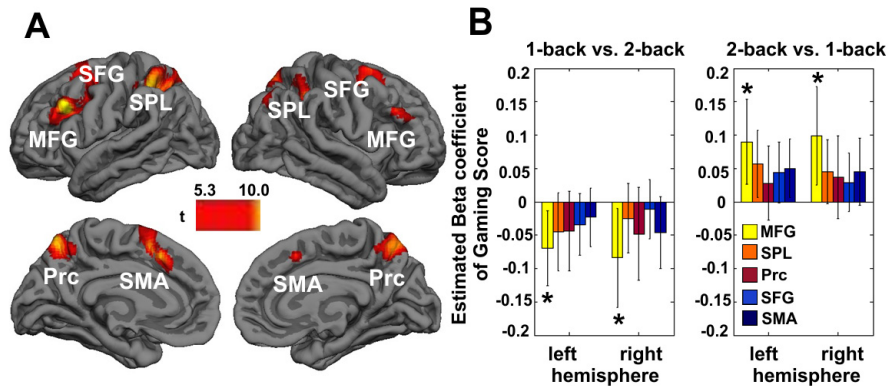


Figure 9. (A) Cortical regions showing greater activity during a conjunction of 2-back and 1-back activity than during 0-back comprised of frontal and parietal cortical regions (i.e., WM ROIs). Voxel-wise height threshold $t=5.26$, cluster size > 100 , voxel-level Familywise error corrected $p < 0.05$. (B) Activity in the middle frontal gyrus (MFG) ROI of each hemisphere demonstrated a significant main effect of Gaming Score, so that the higher the Gaming Score of a participant, the smaller the change in MFG activity from 0-back to 1-back, but the greater the change in MFG activity from 1-back to 2-back. Significant standardized beta values for Gaming Score produced by the General Linear Model for activity in each of the WM ROIs (while controlling for Gender, age, DA Score and GPA) are indicated with asterisks ($* p < 0.05$). Error bars represent 95% confidence intervals. (MFG = middle frontal gyrus, SPL = superior parietal lobe, Prc = precuneus, SFG = superior frontal gyrus, SMA = supplementary motor area)

Consistent with previous results (Blacker & Curby, 2013; Boot et al., 2008; McDermott et al., 2014; Sungur & Boduroglu, 2012), our study suggests that gaming activity is linked to better working memory performance, seen as improvements in performance accuracy and in the speed of correct responses irrespective of the presentation modality of the task. This lends support to the notion that gaming experience is related to

general aspects of working memory, such as the ability to remove irrelevant items from working memory effectively, or the ability and update working memory content (Colzato et al., 2013). Furthermore, gaming was found to be associated with reduced costs of switching between audition and vision during working memory task performance. This result demonstrates that the improved recovery from attention shifts that has previously been linked to gaming (Colzato et al., 2010; Karle et al., 2010; Cain et al., 2010; Green et al., 2012) also applies to modality switches between sensory modalities while working memory is simultaneously taxed. Importantly, no age-related influence on the relationship between gaming and improved working memory were observed, suggesting that the coupling between gaming and cognition is detectable already in adolescence. Further, the working memory improvements noted in the study were not specific to any certain type of game, suggesting that common features of the gaming experience are most relevant to the more general aspects of working memory functioning observed here.

The observed behavioral improvements linked to gaming were coupled with differences in the recruitment of dorsolateral prefrontal regions so that during the less demanding task level, gaming was related to decreased activity, but the opposite was true when the task became more challenging. The observed pattern of cortical recruitment is not easy to interpret in light of existing evidence, as previous studies on memory training have shown both increased activity in prefrontal, parietal and occipital cortices (Nyberg et al., 2003; Olesen et al., 2004) and the striatum (Dahlin et al., 2008), as well as with decreased activity (Dahlin et al., 2009) or no changes in cortical activity at all (Nussbaumer et al., 2015) after training. Furthermore, activity changes in working memory associated brain regions as a result of training have been shown to vary individually, so that these individual differences predict performance in untrained working memory tasks (Nikolaidis et al., 2014). The results of the current study may, however, be explained by the moderating effect of task difficulty. During relatively easy tasks, individuals with a greater cognitive capacity may need to recruit less cortical resources to achieve the same behavioral performance level as other individuals. In contrast, as task difficulty increases, these individuals recruit task-relevant brain regions to a greater extent and exhibit superior performance, perhaps because a different cognitive strategy is used to accomplish the task (Rypma et al., 2002). The use of more efficient organization strategies could explain why we observed significant effects only in dorsolateral prefrontal regions, as these regions have been shown to play an essential role in organizing working memory content (Bor et al., 2003, 2004; Owen et al., 1996). In line with our results, previous studies have also linked more efficient working memory functioning to the upregulation of prefrontal activity specifically in response to higher task demands (Nagel et al., 2011; Nyberg et al., 2014). Overall, the results of the current study shed more light on the relationship between load-related changes in brain activation and task performance.

5 GENERAL DISCUSSION

5.1 Cortical networks of working memory and attention

In the studies of the present thesis, attention and working memory tasks were used to map out cortical networks related to selective and divided attention, attentional shifting, and working memory. In line with a vast amount of accumulated research, our studies further confirmed that both attentional and working memory processes activate medial and lateral regions of the frontal and parietal cortices of the human brain. The commonly held view that a “frontoparietal control network” is crucial to all executive processes (Badre & D’Esposito, 2007; Vincent et al., 2008) was therefore supported by the results of the present studies.

Both the auditory-visual working memory task as well as the attention task involving selective and divided attention to sentences activated largely overlapping cortical regions: the dorsolateral prefrontal cortex bilaterally (especially the middle frontal gyrus; MFG), the superior parietal lobule (SPL), as well as the supplementary motor area (SMA). The dorsolateral prefrontal cortex is known to be strongly involved in top-down executive control processes, especially in the right hemisphere (Garavan et al., 1999; Aron et al., 2003; Fassbender et al., 2006). The MFG in particular has also been linked to memory rehearsal processes (Awh et al., 1996), rapid adaptation and coordination of actions required in dual-tasking (Szameitat et al., 2002), and detection of unexpected relevant stimuli (Corbetta & Shulman, 2002), all of which are processes invoked by the tasks used in our studies. SPL regions, in turn, have most often been linked to top-down controlled spatial and non-spatial attentional shifting of both auditory and visual attention (Salmi et al., 2009; Shomstein & Yantis, 2006; Wu et al., 2007). It seems, however, that these parietal regions are also activated during bottom-up triggered attention shifts (Kim et al., 1999; Rosen et al., 1999; Salmi et al., 2009). It is therefore possible that either endogenously or exogenously regulated shifts in attention between the sensory modalities explain the observed SPL activity, since both the attention task and working memory task involved visual and auditory stimuli which were presented simultaneously or in succession, respectively. Finally, the SMA has been shown to be involved in aspects of response selection, such as performance monitoring, pre-response conflict, decision uncertainty and response errors (Ridderinkhof et al., 2004). The need to inhibit prepotent responses or the overall difficulty in choosing the correct response during both the attention and working memory tasks may therefore explain why this region was consistently activated across task types.

In addition to the regions outlined above which were commonly activated by both task types, the working memory task used in **Study III** activated an additional cortical region, the precuneus. Although precuneus functioning is most often associated with processes such as visuospatial

imagery, episodic memory retrieval and self-referential processing (see Cavanna & Trimble, 2006), it has nonetheless been shown to also play a crucial role in working memory functioning. For example, the precuneus has been shown to be selectively activated by a verbal working memory task when compared with spatial attention task (LaBar et al., 1999), and a meta-analysis of 24 *n*-back studies found the precuneus to be one of the few regions consistently activated across all studies (Owen et al., 2005). It is therefore not surprising to see that this region was selectively recruited by the working memory but not the attention task in our studies. Another noteworthy difference was that the working memory task activated a more dorsal portion of the prefrontal cortex, whereas frontal activity during the attention task extended more ventrally into the inferior frontal gyri (IFG). This is most likely due to differences in the nature of the stimuli: unlike in the attention task, matching letters to one another in the working memory task required no semantic linguistic processing. It is therefore likely that the more inferior frontal activity observed only for the attention task was related to having to judge the congruency of the presented sentences. This is because previous studies using semantic congruence manipulations have consistently observed greater hemodynamic activity for incongruent than congruent sentences in the IFG, both when the sentences are presented as written text (Baumgaertner, 2002; Kuperberg et al., 2002) and when they are presented as speech (Ni et al., 2000; Cardillo et al., 2004). This is supported by our own analyses from **Study I**, which demonstrated greater activity in the IFG in response to incongruent than congruent sentences.

5.2 Neural underpinnings of multitasking limitations

Humans are known to exhibit slower and more error-prone performance when carrying out two tasks simultaneously than when performing the same tasks separately. Several competing proposals have been made concerning the level at which competition occurs when two tasks are performed in parallel. It has been suggested that the main limiting factor is a central bottleneck in executive task-coordination systems recruited specifically by multitasking (D'Esposito et al., 1995; Collette et al., 2005). Interference may also be generated at the level of the sensory cortices, where during multimodal divided attention the sensory cortices have to compete for shared and limited attentional resources (Näätänen, 1992). Finally, if the component tasks require similar processing and therefore rely at least partly on the same cortical regions, multitasking may lead to competition for the use of those common regions (Roland & Zilles, 1998).

In **Study I**, we aimed to further investigate the neural underpinnings of multitasking limitations by measuring brain activity while healthy adult participants performed a sentence congruency judgement task either in one modality at a time, or in two modalities simultaneously. Our results demonstrated firstly, that crossmodal inhibition of the sensory cortices was

not responsible for the observed performance decrements during multitasking. Secondly, no areas were recruited during divided attention that were not already activated when the component tasks were performed separately. It is therefore more likely that a surplus of activity in lateral and medial prefrontal regions, rather than recruitment of specialized multitasking regions, contributes to multitasking limitations. Finally, our results regarding activity in language-related regions lead us to conclude that competition for resources in semantic processing areas used by both component tasks is also a likely contributing factor to multitasking performance decrements.

Some studies have reported opposing results, showing that frontal regions are recruited only during divided attention (Corbetta et al., 1991; Miyake et al., 2000; Herath et al., 2001; Szameitat et al., 2002; Johnson & Zatorre, 2005; Stelzel et al., 2006), leading researchers to suggest that multitasking recruits specialized task-coordinating systems which are not needed when only one task is performed at a time. These conflicting results may be explained more by the nature of the component tasks used in the individual studies than by the need to divide attention *per se*. Frontal recruitment may vary from one task combination to the other depending on the specific features of the component tasks (Salo et al., 2015). In our study, the component tasks recruited frontal regions already during selective attention, possibly both because the stimuli in the attended modality had to be actively selected for further processing while the stimuli of the unattended modality were to be ignored, and because the stimuli to be unattended caused unintentional attention shifts away from the attended stimuli. It could also be argued that since our component tasks were complex sentence evaluation tasks, performing them under the selective attention condition was challenging enough to require executive functions to a great degree. This is likely, as that the selective attention condition was observed to result in worse performance and increased activation in frontal cortical regions when compared with the unimodal condition. Our results may also be explained by the fact that many of the previous studies examining multitasking effects have used component tasks that do not require similar processing (e.g., a spatial rotation and a semantic judgment task; D'Esposito et al., 1995) and therefore do not necessarily compete for activation in the same cortical regions. In our study, however, both component tasks required semantic processing and we were therefore more likely to see competition at the level of task-specific regions. It is obvious that the neural factors limiting multitasking performance may depend largely on the nature and difficulty of the component tasks. Future studies would benefit greatly from examining more carefully the effects of different task combinations on multitasking.

5.3 Associations between technology use and executive functions

The relationship between different types of daily technology use on attention and working memory functioning was investigated in **Study II** and **Study III**. This was achieved by recording the performance and brain activity of adolescent and young adult participants as they performed cognitive tasks taxing executive functions, and by relating these indices to their self-reported daily technology-mediated activities. In **Study II**, we looked specifically at the relationship between daily media multitasking activity and attentional functioning, as previous studies have demonstrated links between the two phenomena (Alzahabi & Becker, 2013; Ophir et al., 2009; Loh & Kanai, 2014; Yap & Lim, 2013). In **Study III**, the level of the participants' gaming activity was compared to their performance and brain activity during a working memory task, as gaming has been suggested to train working memory abilities (Blacker & Curby, 2013; Colzato et al., 2013; McDermott et al., 2014).

In both studies, associations were found between the technology-mediated activities, task performance and brain activity in frontoparietal regions, but in opposing ways. In **Study II**, media multitasking was found to be negatively correlated with performance accuracy specifically when attention on a focal task was disrupted by the presentation of a distractor in a to-be-ignored modality. Furthermore, this distractibility was coupled with enhanced activity in right prefrontal regions. Media multitasking has been shown to be linked to distractibility in a previous study (Ophir et al., 2009), but the present study extended those findings in three important ways. First, we were able to demonstrate that distractibility is associated with media multitasking already during middle adolescence, whereas the study by Ophir and colleagues (2009) was limited only to adult participants. Second, we were able to detect this association by using a more ecologically valid attention task than those used by Ophir and colleagues (2009). Third, our study is the first to include measures of brain activity and not only behavior, thus elucidating the brain basis of this increased distractibility. In **Study III**, we were able to demonstrate a positive association between gaming activity and working memory performance as well as the ability to switch between sensory modalities at unpredictable intervals. A further finding was that these behavioral enhancements were linked to the recruitment of frontal regions, so that activity in these regions increased during the most demanding level of the working memory task. This study was the first of its kind to examine brain activity using fMRI during a working memory task in relation to gaming experience in adolescents and young adults.

Considering how much time the adolescents and young adults of today spend interacting with technology (approximately 7.5 hours every day as estimated in 2010; Rideout et al., 2010), the findings of **Study II** and **Study III** are of extreme importance. This is because they suggest that different

types of technology-mediated activities may potentially have measurable effects on cognitive functioning and brain activity of young people. It is important to note, however, that the effect sizes in both studies are consistently small. This means that significant effects are only detected when data from a large number of participants is pooled together, and the results therefore tell us very little about each individual.

Interestingly, no significant interacting effect of the age of the participants was observed, suggesting that associations between cognitive function and technology use are detectable already in early adolescence. It is also possible that the effects of technologically-mediated activities studied here may actually be tied to the trajectory of cortical development. For example, the immaturity of prefrontal regions (irrespective of age) might be reflected both as an inadequate ability to inhibit unwanted attentional shifts, which may be reflected both as more media multitasking in daily life, and as increased frontal activity during a demanding attention task. This hypothesis is not directly supported by our data, however, as no differences between the amount of daily media multitasking activity was noted between the three studied age cohorts. Future studies might benefit from recruiting even younger participants than those of the current studies in order to determine at what age the observed associations become detectable, or by utilizing longitudinal datasets in order to track more subtle interactions between technology use and age-related changes in cognitive functioning as well as individual trajectories of brain development.

Due to the correlational nature of both studies, longitudinal data is needed in order to confirm the direction of causality between technology use and cognitive performance. Before the cause can be unequivocally disentangled from the effect, several alternative explanations can be given to the results obtained from the studies. The results from **Study II** may be explained by the fact that extensive daily media multitasking directly reinforces task switching behavior and deteriorates the ability to sustain attention on a focal task. Frequent daily multitasking behaviors may, in other words, lead to reduced cognitive control and greater susceptibility to interference (Carr, 2010; Loh & Kanai, 2015). However, an equally plausible explanation for the results is that decreased executive functioning leads to more media multitasking activity. In a similar vein, the behavioral results of the **Study III** can either be explained by the fact that gaming activity enhances executive functions due to the cognitively demanding aspects of the fast-paced virtual gaming environment (Anguera & Gazzaley, 2015), or alternatively, by the fact that pre-existing differences in cognitive ability affect how much time individuals spend gaming in daily life.

A few considerations related to brain plasticity can help to form tentative hypothesis about the direction of causality between technology use and cognitive functioning. In general, the brain is known to retain plasticity throughout the lifespan and rehearsal is known to lead to structural changes in the brain (Zatorre et al., 2012). Experience-related changes have been

shown to occur even in the adult brain as a result of perceptual (Chen et al., 2016; Golestani & Zatorre, 2004; Kuai et al., 2013; Winkler et al., 1999) or skill learning (e.g., Boyke et al., 2008; Maguire et al., 2000). The issue of whether executive functions can be improved with targeted cognitive training is less clear. There is evidence that training can be used to enhance working memory (Harrison et al., 2013; Toril et al., 2016; von Bastian & Oberauer, 2013), as well as multitasking and task switching abilities (Cepeda et al., 2001; Minear & Shah, 2008; Lussier et al., 2012; Strobach et al., 2012). This suggests that computerized training regimes could indeed have an impact on at least some aspects of cognitive functioning. This might also apply to gaming, since some evidence exists to suggest that training non-gamers on action video games has been shown to lead to cognitive benefits (Green & Bavelier, 2003) even when the participants have been older adults (Anguera et al., 2013; Belchior et al., 2013). Games may, in other words, act as a cognitive enhancement tool, even though that is not the purpose that they have originally been designed for (Anguera & Gazzaley, 2015). If that is the case, then the results of **Study III** might reflect an enhancement in working memory that is a direct result of gaming exposure. Media multitasking, in turn, is more difficult to study than gaming using carefully controlled training paradigms for several reasons. Firstly, most people indulge in media multitasking to some degree in their daily lives, so assuming that one can expose participants to media multitasking only within the confounds of the laboratory is unrealistic. Further, it is still unclear whether media multitasking in daily life is a result of voluntary (albeit frequent) shifts of attention, or due to an inability to inhibit attention shifts to salient events in the environment. Evidence for both possibilities exists since media multitasking has been linked both to an improved ability to switch between tasks when cued (Alzahabi and Becker, 2013), and to increased task switching costs and an inability to ignore distractors (Ophir et al., 2009), the latter being also indicated by the present **Study II**. If the source of media multitasking behavior is indeed related to exogenous shifts of attention, experiments where this type of attention orienting could (or should, for that matter) be trained are difficult to conceive. A more appropriate approach would then be to use longitudinal study designs to see if attentional control deteriorates over time as the time spent media multitasking in everyday life accumulates. Longitudinal data has, in fact, been gathered from the participants of **Study II** and **Study III**, and our aim is to track how both media multitasking and gaming continue to interact with cognitive abilities in these participants over time.

Despite the findings accumulated so far, more strictly controlled studies are needed in order to make inferences about the relationship between technology-mediated activities and cognition. In addition, more accurate ways of measuring daily interactions with technology (such as experience sampling) could also be used alongside self-reporting. Furthermore, other brain imaging modalities (such as EEG or MEG) could be

used to study aspects of brain activity which remain elusive in the current studies, such as the effects of technology use on the temporal dynamics of activity in frontoparietal regions during cognitively demanding tasks.

6 CONCLUSIONS

The present thesis investigated the cortical networks recruited by attention and working memory tasks, and examined the relationship between technology-mediated activities, performance and brain activity during these tasks in adolescents and young adults. The results demonstrated that a common frontoparietal network was broadly activated across task types, although some regions were selectively activated by the working memory task. Divided attention was studied in relation to selective attention, and surplus frontal activity and competition within cortical regions recruited by both component tasks were identified as a major factor limiting multitasking performance. During selective attention when the focal task was presented with a distractor, performance accuracy decreased and more frontal activity was observed than when no distractor was present. Self-reported daily media multitasking activity was found to be associated with worse performance specifically during the selective attention condition, and also with recruitment of cortical regions known to be important for attentional control, possibly reflecting increased effort during task performance. Conversely, gaming activity was positively related to working memory performance and to the ability to switch attention between sensory modalities during the most demanding level of the task, and this was coupled with enhanced recruitment of task-related brain regions. Future studies would benefit greatly from using longitudinal study designs and training paradigms in order to further investigate the direction of causality between different types of technology use and cognitive functioning.

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