Role of Oscillations in Visual Perception: Attention and Working Memory

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CONTENTS

Contents ................................................................................................................................. 3
List of publications .................................................................................................................... 5
Abbreviations ........................................................................................................................ 6

1 Abstract ............................................................................................................................... 7

2 Tiivistelmä ......................................................................................................................... 8

3 Introduction ....................................................................................................................... 9
  3.1 Oscillatory activity .................................................................................................... 9
  3.2 Visual attention ........................................................................................................ 11
  3.3 Visual working memory ......................................................................................... 12
  3.4 What is measured with MEG and EEG ............................................................. 14

4 Aims ................................................................................................................................ 15

5 Methods ........................................................................................................................... 16
  5.1 Subjects .................................................................................................................... 16
  5.2 Tasks ......................................................................................................................... 16
  5.3 Recording equipment ............................................................................................ 17
  5.4 Data Preprocessing ............................................................................................... 17
  5.5 Behavioral performance ....................................................................................... 17
  5.6 Source modeling ..................................................................................................... 17
  5.7 Signal analysis ......................................................................................................... 18
  5.8 Functional landmarks (for Study III) .................................................................. 19
  5.9 Statistical analysis ................................................................................................. 19

6 Results / Summary of publications .................................................................................. 20
  6.1 Behavioral performance ......................................................................................... 20
  6.2 Study I common attentional load effects ............................................................ 20
  6.3 Study I attentional load effects differences between capacity groups .......... 22
  6.4 Study II common attentional load effects ............................................................ 22
  6.5 Study II attentional load effect differences between capacity groups .......... 24
  6.6 Study III differences between loads 2 and 4 .................................................... 25
LIST OF PUBLICATIONS

The articles this thesis is based on are referred to with roman numerals:


II. Rouhinen S, Siebenhühner F, Palva JM, Palva S. 2018. Spectral and anatomical patterns of large-scale synchronization predict human attentional capacity. UNDER REVISION.


Author’s contribution to the studies to the thesis:

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Study II: Measured subjects, data preprocessing, data analysis with FS, wrote visualization software, manuscript writing with FS, SP and JMP.

Study III: Statistical analysis and visualization with RH, manuscript writing with RH, SHW, JMP and SP.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CFS</td>
<td>Cross-frequency synchrony</td>
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<tr>
<td>CO</td>
<td>Cingulo-opercular</td>
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<tr>
<td>DLPFC</td>
<td>Dorsolateral PFC</td>
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<tr>
<td>EEG</td>
<td>Electroencephalogram</td>
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<tr>
<td>FEF</td>
<td>Frontal eye-field</td>
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<tr>
<td>fMRI</td>
<td>Functional MRI</td>
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<tr>
<td>FP</td>
<td>Fronto-parietal</td>
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<td>IPS</td>
<td>Inferior parietal sulcus</td>
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<tr>
<td>LO</td>
<td>Lateral-occipital</td>
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<tr>
<td>LPFC</td>
<td>Lateral PFC</td>
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<tr>
<td>MEG</td>
<td>Magnetoencephalogram</td>
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<tr>
<td>meOTS</td>
<td>Medial occipitotemporal sulcus</td>
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<tr>
<td>MOT</td>
<td>Multiple object tracking</td>
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<tr>
<td>MRI</td>
<td>Magnetic resonance imaging</td>
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<tr>
<td>MT</td>
<td>Visual area middle temporal (V5)</td>
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<tr>
<td>PAC</td>
<td>Phase-amplitude coupling</td>
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<tr>
<td>PFC</td>
<td>Prefrontal cortex</td>
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<tr>
<td>PLV</td>
<td>Phase-locking value</td>
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<tr>
<td>PPC</td>
<td>Posterior parietal cortex</td>
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<tr>
<td>SD</td>
<td>Standard deviation</td>
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<tr>
<td>SM</td>
<td>Somato-motor</td>
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<tr>
<td>T1</td>
<td>Task 1 of Study I and II, no distractors</td>
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<tr>
<td>T2</td>
<td>Task 2 of Study I and II, distractors present</td>
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<tr>
<td>TPJ</td>
<td>Tempero-parietal junction</td>
</tr>
<tr>
<td>V1</td>
<td>Visual area 1</td>
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<tr>
<td>V4</td>
<td>Visual area 4</td>
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<td>VWM</td>
<td>Visual working memory</td>
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1 ABSTRACT

People have large differences in their visual attentional and working memory (WM) abilities. Both attention and WM are thought to comprise of representation of sensory information and its attentional / executive control. A common finding is that people’s ability to attend to or to memorize several items concurrently ranges from 2 to 4 items. How attention and working memory functions arise from distributed brain activity and what mechanisms limit the attentional and working memory capacity are largely unknown.

In this thesis, concurrent magnetoencephalography and electroencephalography (MEG and EEG) recordings of whole brain activity combined with source modeling were used to study the role of rhythmic cortical activity in attention and WM. Visual attention was studied with a multiple object tracking task (MOT), where the subjects tracked 1–4 moving target objects with and without distracter objects. The functional role local oscillations amplitudes as well as the significance of large-scale inter-areal synchronization in setting the capacity of visual attention were studied. We found a decrease in oscillation amplitudes at relatively lower frequencies (alpha–beta), and an increase at higher frequencies in the gamma band (30–90 Hz) as a function of attentional load. The load-dependent oscillation amplitude modulations differed in better and worse performing subjects (i.e. subjects with high and low attentional capacity, respectively). In high-capacity subjects, gamma amplitudes increased more strongly as a function of load in widespread cortical regions including lateral PFC, temporal and visual areas, whereas in the low capacity subjects load-dependent gamma amplitude increase was smaller. Large-scale inter-areal synchronization was found at low theta (4–5 Hz) and high-gamma (70–90 Hz) bands. The most robust connections were observed between the left and right PFCs and between visual areas and PFC. The load-dependent strengthening in inter-areal synchronization differed between high and low capacity subjects at several frequencies. These results suggest that both local and inter-areal rhythmic activity differences can explain differences in attentional capacity.

Visual working memory was studied with a delayed match-to-sample WM task, where different visual features or their conjunctions were retained in WM. The functional role of load-dependent oscillation amplitudes in remembering different features were studied. Distinct load-dependent differences in local gamma-band amplitudes were found to reflect maintenance of specific visual features in WM. Gamma band oscillations were also increased for the memorizing the conjunction of features supporting their role in binding of visual features. These results suggest that especially rhythmic gamma activity is important in maintaining visual information WM.

Taken together our results suggest common mechanisms for visual attention and VWM, and that gamma oscillations work in a highly task specific manner, and that gamma oscillations are critical for perception.


Näkötyömuistikokeessa havaittiin, että näköärsykkeiden erilaisten ominaisuuksien mielessä pitäminen vastasi erilaisia paikallisia gamma-aktiivisuus -vasteita niin ajoituksen kuin aivoalueiden mukaan. Lisäksi havaittiin, että gamma-aktiivisuus on tärkeää erilaisten näköärsykkeominaisuuksien yhdistämisessä.

Nämä tulokset viittavat siihen, että näkötarkkaavaisuudella sekä –työmuistilla on ainakin osittain sama perusta, rytminen gamma-aktiivisuus on hyvin tehtävääriippuvaista, ja että rytminen gamma-aktiivisuus on kriittistä havainnoimisessa.
3 INTRODUCTION

Studying the brain is interesting. As the knowledge about how the brain works increases, we for example understand that epilepsy can be treated by inhibiting flaring of excited brain activity either by medicine or surgery, instead of exorcising evil spirits. Despite of a lot of research (search for brain gives over 1.5 million results in PubMed) there is much unknown about the neural basis of cognitive functions. Normal brain activity encompasses many cognitive functions, of which attending to multiple targets and keeping in mind visual features are the focus in this work.

There is great variability between people in different attributes like height, dexterity, and mental attributes like the capacity of visual observation, and keeping in mind what was previously seen. Depending on the task and individual, there are enough visual attentional resources to attend successfully to 2–4 targets at the same time. A similar range has been found for retaining visual objects in memory.

Current hardware and software tools allows sophisticated analysis of brain activity. One can use MEG and EEG to measure the brain’s weak magnetic and electrical activity with great temporal resolution. MEG and EEG measure from outside of the scalp and from the scalp so they are easy to use, but the sensor level data is only very roughly localizable to any part of the brain. With MRI one can measure the anatomy of an individual’s brain with good spatial resolution. Combining the MEG and EEG and MRI allows one to estimate brain activity (using source modeling) with the timescale resolution relevant to the brain itself, and with decent ability to estimate where in the cortex the activity is happening.

This thesis addresses what kinds of rhythmic or oscillatory activity in the brain correlates with visual attentional load, good versus poor attentional performance, retention of separate visual features, and difference between retention of visual features at the same time compared to separate retention.

3.1 OSCILLATORY ACTIVITY

Distributed activity between separate brain areas needs to be coordinated in some way. One way to coordinate distributed neuronal activity is through coincident firing of the cell populations (Bender et al., 2006; Joris et al., 1998). Coincident and rhythmic firing has been studied famously in cats and monkeys. This rhythmic coincident firing is called zero-lag oscillatory activity. Single column synchrony at gamma frequency could be observed in cats’ visual cortices when they were shown moving or stagnant light bars (Gray and Singer 1989). Strongest inter-column synchrony could be observed in the visual cortex when cats observed a single bar moving spanning the receptive field of two recording sites, intermediate synchrony for two bars moving in the same direction, and no synchrony when the bars moved in opposite directions (Gray et al., 1989). Similar results have also been observed in monkeys (Kreiter and Singer 1996; Livingstone 1996) and with and without anesthetization (Gray and Viana Di Prisco 1997). This synchrony has been suggested to bind activity in separated brain regions (Singer 1999; Varela et al., 2001).
Rhythmic activity can also be observed non-invasively with MEG and EEG. The rhythmic or oscillatory activity is defined with frequency, phase and amplitude. Frequency is the rate of cycles per second (Hz). Phase is the time point in an oscillation. One oscillation cycle’s phase is divided into 360°, usually expressed in radians. Amplitude is the magnitude of the extreme values of the oscillation. To extract amplitude, phase and frequency one needs to transform the signals into complex form. One of the ways to do this is to use Hilbert transform with Morlet wavelet convolution to create an analytic signal. There are many definitions of amplitude. In this thesis peak amplitude is used, or more exactly the absolute value of the analytic signal.

The observed rhythmic activity is sporadic with the frequency and amplitude of brain’s oscillatory activity changing, and several different frequencies can be observed at the same time. Commonly studied frequencies range from around 4 Hz to 150 Hz. These frequencies are divided into frequency bands: theta (4–8 Hz), alpha (7–15 Hz), beta (15–30 Hz), and gamma (30–150 Hz). There is some variation in to what frequencies different people place the frequency bands, but these ones should be rather uncontroversial. Considering the prior experiments (Axmacher et al., 2008; Bae and Luck 2018; Barnes et al., 2016; Crespo-Garcia et al., 2013; Gray and Singer 1989; Gruber et al., 1999; Haegens et al., 2011; Jensen et al., 2002; Jensen and Mazaheri 2010; Klimesch et al., 2007; Magen et al., 2009; J. M. Palva et al., 2010; S. Palva et al., 2011; Polania et al., 2012; Siebenhüchner et al., 2016; Siegel et al., 2008; Tallon-Baudry et al., 1998; Wyart and Tallon-Baudry 2008) I consider alpha and gamma activity to be particularly pertinent frequency bands for attention and working memory.

Synchrony between two brain areas can be estimated with amplitude and phase. A usual way is to look at how of the signals between the two brain areas co-vary. If the areas have exactly similar signals in time, they are synchronous. If they have completely unrelated signals they are not synchronous. The former situation with the same signals would get a synchrony value of 1, and the latter situation would get a synchrony value of 0. In brain data you will get values between 0 and 1. Using phase to estimate synchrony between the areas is a common method. If the brain areas have a consistent phase relation they are considered to synchronize. This can happen at a certain time of a task for example, with the synchrony being lower at other times of a task. Or synchrony between brain areas might increase as a function of task difficulty. In these cases where synchrony increases one would consider synchrony playing an important role.

Though the most common way to estimate synchrony is phase-phase synchrony with 1:1 frequency ratios, one can also estimate n:m ratio cross-frequency synchrony (CFS), and phase-amplitude coupling (PAC). Cross-frequency synchrony is estimated in a similar fashion to 1:1 synchrony, but just between different frequencies like 10 Hz and 20 Hz (ratio 1:2) (for review (J. M. Palva and Palva 2017)). In PAC the relationship between the amplitude of a higher frequency and the phase of a slower frequency is estimated (rev (Canolty and Knight 2010)).

The functions of different frequencies and measures are discussed in chapters 3.2 Visual attention and 3.3 Visual working memory.
3.2 **Visual Attention**

In natural situations there are many objects and locations that one might need to respond to. Humans have an individually varying and limited ability to attend and track around 2–4 visual objects (Bettencourt et al., 2011; Cowan 2001; Oksama and Hyona 2004; Pylyshyn and Storm 1988). Due to limited attentional resources the resources need to be guided to relevant objects and locations and non-relevant features need to be ignored. Tracking a subset of objects among many objects requires selecting and sustaining attention on the selected objects (Alvarez and Cavanagh 2005). Attention can be directed in a top-down or goal-directed manner, and it can also be directed in a bottom-up or stimulus driven manner (Kastner and Ungerleider 2000). Attention to relevant instead of irrelevant objects and locations are associated with strengthened neuronal activity to attended and decreased neuronal activity with ignored objects and locations (Corbetta and Shulman 2002; Kastner and Ungerleider 2000; Miller and D’Esposito 2005; Reynolds and Chelazzi 2004; Serences and Yantis 2006).

At the neuronal level attention has different effects on the activity at different brain areas and the neuronal modulations are rather complicated. At a high level area frontal eye-field (FEF) of macaques putative interneurons show stronger attentional modulation effect than putative pyramidal cells (Thiele et al., 2016), with attention having a stabilizing effect rather than firing rate change effect. Greater FEF activity corresponds to faster visual search, and modulates V4 activity in a top-down biasing manner (Zhou and Desimone 2011). In V4 of macaques’ attention reduces activity of unattended items in the receptive field but does not enhance responses to attended stimuli (Moran and Desimone 1985). So, attention seems to filter out irrelevant information within the receptive field, but has little effect outside of the receptive field. In MT and medial superior temporal area of macaques’ attention enhances neural responses to targets compared to non-targets, whereas non-target distractor dots have reduced responses when there is a target at the same time (Treue and Maunsell 1996).

Expanding the view from the neuronal level to the systems level fMRI studies have revealed that multi-object attention in posterior parietal and prefrontal cortices is correlated with attention towards multiple stimuli (Corbetta and Shulman 2002; Kastner and Ungerleider 2000). Attentive tracking compared to passive viewing of multiple stimuli increases activity in prefrontal cortex (PFC) and posterior parietal cortex (PPC) (Culham et al., 1998; Jovicich et al., 2001). Oscillatory activity at several different frequencies has been associated with attentional effects. High frequency gamma-band amplitudes are strengthened by attention in different types of attentional tasks. This modulation by attention has been observed for spatial (Gruber et al., 1999; Siegel et al., 2008; Wyart and Tallon-Baudry 2008), feature-based (Muller and Keil 2004), and audio-visual attention (Kaiser et al., 2006). Beta oscillations have been suggested to promote feedback influence (Fries 2015). Increased alpha-band amplitudes are usually considered as inhibiting task-irrelevant objects and features (Klimesch et al., 2007; Pfurtscheller 2003; Ray and Cole 1985; Sauseng et al., 2009). Alpha-band oscillations are suppressed in visual cortex contralateral to the attended visual hemifield and enhanced ipsilateral to the attended hemifield (Klimesch et al., 2007; Thut et al., 2006; Worden et al., 2000). Though there is alpha band suppression in the early visual areas, alpha-band amplitude is strengthened in higher visual or association areas and frontal areas during spatial detection tasks (Haegens et al., 2011), and audio-
visual attention tasks (Mo et al., 2011). Pharmaco-electrophysiological studies show that alpha band oscillations are not only inhibitory (Lozano-Soldevilla et al., 2014; Lozano-Soldevilla 2018). Inter-areal distributed processing is thought to be coordinated by large-scale neuronal synchronization (Fries 2015; Siegel et al., 2008; Womelsdorf and Everling 2015). In invasive animal recordings beta- and gamma-band synchronization has been observed to strengthen between visual regions and PPC by attention (Buschman and Miller 2007; Womelsdorf and Fries 2006; Womelsdorfe et al., 2006). Inter-areal neuronal synchronization and phase coupling in non-invasive recordings of humans has been shown to coordinate visuospatial attention (Doesburg et al., 2016; Lobier et al., 2018; Siegel et al., 2008). Attention in a serial task has been observed to increase beta-band synchronization between frontal, parietal and temporal regions (Gross et al., 2004). Attention in a visuospatial task had attentional modulations between frontal, parietal and visual regions with the modulations having rather varied spectral patterns between the different areas (Siegel et al., 2008). Cross-frequency synchrony between theta and gamma was observed to be enhanced by attention in a spatial attention task (Sauseng et al., 2008).

3.3 VISUAL WORKING MEMORY

VWM can be defined as active maintenance of visual information online to serve in performing ongoing tasks (Luck and Vogel 2013; Persuh et al., 2018) and is important for general cognitive ability (Johnson et al., 2013). To say this more specifically for VWM, the memory must be visual (not say verbal), VWM is based on neural activity (instead of for example synaptic structural changes), and serves broader cognitive tasks. VWM is conscious and there seems to be little evidence for unconscious VWM (Persuh et al., 2018).

Objects in VWM seem to be stored as whole objects or chunks instead of as a collection of feature atoms stored in a continuous resource (Luck and Vogel 1997; Wheeler and Treisman 2002; Zhang and Luck 2008). The objects are not stored with perfect precision, so there is some variability in the encoding of objects to VWM (Ronald van den Berg et al., 2012). The WM resources can be divided unequally to different objects, making a strong case for the resource model instead of the slot model (Ma et al., 2014). In the slots model WM has X slots where one item takes one slot, and keeping multiple items in WM takes as many slots. In the resource model there is a pool of resources that can be divided flexibly between items to be kept in WM. The items that get more resources will be kept in WM better than items that get fewer resources. The capacity of VWM is about 3–4 objects (Vogel and Machizawa 2004; Vogel et al., 2005) which is similar to visual attentional capacity. This has led to experimenters testing if attentional limit is what limits VWM (Rev (Cowan 2001)). Capacity is an estimate of how many objects can be kept in mind that is based on performance in an experiment. While attention is a critical part of VWM capacity, there seem to be also a central amodal supervisory process, and VWM content-specific stages of operations that limit the VWM capacity (Fougnie and Marois 2006). Using only psychophysics to come up with a theory of how capacity limits are set is very challenging (Cowan 2001). Using electrophysiology will help in finding out what brain functions drive VWM.
Activity associated with VWM is widespread in the brain (D’Esposito and Postle 2015; LaRocque et al., 2013). Object representations are constructed widespread in the visual system (Kravitz et al., 2013). Attentional and executive functions related to VWM are coordinated by the frontoparietal network (Fuster 2000; Fuster 2001; Kastner and Ungerleider 2000). Classification tools can be used with high accuracy to decode retained items from the early visual areas (V1-V4) using fMRI, even if early visual areas (V1-V4) are not found to have much increased activity during long retention (Harrison and Tong 2009; Riggall and Postle 2012), but cannot be classified from frontal or IPS areas (Riggall and Postle 2012). However the opposite is true for decoding non-visual properties indicating that the prefrontal cortex is involved in maintaining abstract information (Sue-hyun Lee et al., 2013). In these fMRI studies it has been found that elevated activity reflects non-retention activity like attention, and retention activity may not require elevated activity (LaRocque et al., 2013; Riggall and Postle 2012). The posterior parietal cortex (PPC) limits the capacity of items held in visual memory (Todd and Marois 2004) and perceptual demands during VWM correlate with PPC activity (Morgan et al., 2011). Parietal, prefrontal and visual areas are activated during perception and VWM retention (Larocque et al., 2014). This suggests that memory representations and perceptions rely on same brain areas.

Alpha-band oscillation amplitudes are strengthened in frontal, parietal and higher-level regions during WM (Jensen et al., 2002; Nenert et al., 2012; S. Palva et al., 2011). Alpha-band oscillation amplitudes have been associated particularly with spatial attention in VWM (Bae and Luck 2018). Gamma-band oscillation amplitudes are increased in visual and fronto-parietal areas during VWM maintenance (Jokisch and Jensen 2007; Medendorp et al., 2007; Morgan et al., 2011; S. Palva et al., 2011; Roux et al., 2012; Sauseng et al., 2009). This gamma activity is suggested to be related to perceptual integration and memory maintenance of VWM (Magen et al., 2009; Polania et al., 2012; Tallon-Baudry et al., 1998), particularly in PPC for integration demands (Morgan et al., 2011). Increasing VWM load increases EEG activity until a plateau is reached according to the capacity of the subject (Vogel and Machizawa 2004). Load-dependent gamma amplitude activity predicts accuracy in WM tasks (S. Palva et al., 2011; Roux et al., 2012; Sauseng et al., 2009).

Higher VWM capacity subjects have been found to have greater activity difference between low and high load tasks (Vogel and Machizawa 2004). The difference between high and low capacity subjects might be that high capacity subjects encoded only relevant information, but low capacity subjects’ performance suffered from encoding in to memory also non-relevant information (Vogel et al., 2005). Different frequency bands have been suggested to coordinate processes maintenance (gamma), temporal organization (theta), and inhibition of task-irrelevant information (alpha) in VWM (Roux and Uhlhaas 2014).

Beta and gamma synchronization is related to perceptual binding of feature assemblies in the visual cortex (Singer and Gray 1995; Singer 2013), and in coordinating large-scale networks of visual and fronto-parietal regions (Bosman et al., 2012; Buschman and Miller 2007; Fries et al., 2002; Fries 2005; Gregoriou et al., 2009). During VWM maintenance large-scale gamma-band synchronization is observed in visual and FP areas (Axmacher et al., 2008; J. M. Palva et al., 2010). Long-range alpha synchronization has been suggested to mediate top-down control of WM and serve different function from alpha amplitude modulations (Crespo-Garcia et al., 2013). During VWM maintenance cross-frequency synchronization of theta and alpha to beta and gamma
frequencies has also been observed (Siebenhühner et al., 2016). Phase amplitude coupling during VWM maintenance has been observed with theta and gamma PAC (Polanía et al., 2012), and increased PAC between upper alpha and gamma was observed in children following VWM training, which was associated with improved VWM performance (Barnes et al., 2016).

3.4 WHAT IS MEASURED WITH MEG AND EEG

Single neurons cause very minute electrical currents that can only be measured invasively. One can though measure non-invasively the net activity of several thousands of neurons firing together. The main neuronal activity that is thought to be measurable non-invasively is the net activity of postsynaptic currents of pyramidal neurons on the cortex (M. Hamalainen et al., 1993). The pyramidal neurons are aligned perpendicular to the cortical surface, while most of the other types of neurons are aligned in more random directions (LORENTE de NO 1947). Electric fields of opposing orientations, or fields oriented evenly to all directions will not be measurable outside of the head. As one needs thousands of neurons to create a similar electrical field at the same time, non-aligned neurons are unlikely to create a large enough signal to be measured from outside of the head (Murakami and Okada 2006). A further reason why postsynaptic potentials are what are recorded is they have about 10 times longer half-lives than action potentials, which are too fast for temporal integration (Timofeev et al., 2012).

MEG and EEG activity modeling commonly assumes that the activity visible to the sensors is due to pyramidal neurons, which are oriented perpendicular to the cortical surface ((Niedermeyer et al., 2011) pp. 17–24, 91–94). The electrical field will be aligned with the pyramidal neurons, so fields that EEG measures are commonly modeled to mostly come from gyral sources. This is also due to gyral sources being closer to the scalp so they are attenuated less than deep sources. As the magnetic field is perpendicular to the electrical field, the MEG sensors are thought to catch sulcus wall activity the best, and gyri and deep sulci poorly. MEG catches deep activity poorly, as the strength of a magnetic field drops at a squared rate as the distance grows linearly.

For EEG sensors to measure fields on the scalp arising from the neurons the field must go through flesh, bone, and skin. This causes activity from one point in the cortex to spread to a larger area in the scalp, and so one area in the scalp measures activity from multiple points of the brain. Magnetic fields can penetrate flesh easily so MEG can measure brain activity with greater spatial resolution than EEG, though the difference might not be large in favor of MEG (Cohen et al., 1990). To estimate brain activity instead of sensor activity measured from outside of the head one needs an estimate of how sensor activity corresponds to brain activity. This is done by modeling how active dipoles in the brain would show in the sensors. This is called a forward model or a lead field matrix. The forward model is in turn used with sensor activity metrics to create an inverse model that is a best guess of what brain activity is explained best by sensor activity. As a single activity pattern in the sensors can be explained by several different brain activity patterns, the definition of best will affect how brain activity is evaluated. For example, with minimum norm estimate the brain activity pattern with the least energy will be preferred over other choices (Hämäläinen and Ilmoniemi 1994). See chapter 5.6 Source modeling for details on methods used in this thesis.
4 AIMS

The main aim of the thesis was to study what oscillatory cortical activity explains visual perception. This thesis consists of three studies where visual perception was studied through attention and working memory with concurrent MEG and EEG that was source modeled to reveal cortical level activity.

The aim of study I was to locate attention-dependent local oscillatory amplitude activity during multiple object tracking tasks and ask if the load-dependent oscillatory activity predicts attentional capability.

The aim of study II was to map attention-dependent large-scale synchrony between brain-areas during multiple object tracking tasks and ask if the synchrony predicts attentional capability, and further ask if the load-dependent amplitude results of study I are related to the large-scale synchrony.

The aim of study III was to describe local oscillatory activity related to retaining different visual features during delayed match-to-sample tasks, and ask what activity is required for binding features together.
5 Methods

5.1 Subjects

Studies I and II had the same 19 volunteers as subjects (8 females, mean 26 ± SD 3.5 years). Study III had 13 volunteers (7 females, 29 ± 6 years). The recruited subjects were healthy subjects with normal or corrected to normal vision without glasses. Written informed consent was obtained from each subject prior to the experiment.

5.2 Tasks

In Studies I and II the subjects performed a multiple object tracking (MOT) task in which they attended and tracked visual objects and responded to feature-changes in their shape. We recorded two variations of the task. The first task (T1) was a general attention task where subjects tracked all objects on the screen with the object load varying from one to four. The second task (T2) was an object-selective attention task, where the object load remained at four but subjects attended and tracked only objects with pink color (one to four) while ignoring the objects with yellow color. The objects moved semi-naturally (Dayan et al., 2007). Size of the discs was 0.8 degrees and the vertical size of the display 10 degrees. The objects did not collide with each other or with the screen borders. Inter-stimulus interval ranged from 0.7 to 5 s. After the rejection of target events contaminated by blinks or large eye movements, an average of 133 ± 17 (SD) target events remained in each condition in T1 and 127 ± 29 in T2. For each task and subject, the minimum number of target events across the four conditions was used to obtain an equal amount of events across the conditions.

The VWM experiments of Study III comprised of delayed match-to-sample tasks where the subjects were presented a “sample” stimulus (S1, duration 150 ms) containing randomly either 2 or 4 objects (i.e., VWM loads 2 and 4) either to the left or right side of a fixation dot at the center of the display. The objects were random polygons appearing at different locations and with different colors. In Experiment 1 the subjects memorized either the shapes, colors, or spatial locations of the objects in S1. In Experiment 2, the subjects memorized the color–location conjunctions of these objects. In each trial S1 was followed by a 2.05-s retention period after which a single “test” stimulus (S2, duration 500 ms) was presented. Subjects indicated whether the relevant feature of any S1 was same as or different from S2. The inter-trial interval ranged from 2 to 3 s. The size of the area where the objects were presented was 7.3° × 7.3° and the objects on average spanned an area of 0.65° × 0.65°. After the rejection of target events contaminated by blinks or large eye movements, an average of 656 ± 139 (SD) (shape), 550 ± 211 (color), 610 ± 153 (location), and 1358 ± 205 (joint color-location) trials remained.
5.3 RECORDING EQUIPMENT
Subjects were measured in all studies concurrently with 306-channel MEG, 60-channel EEG, 2 dipole electrooculography (EOG) and 1 or 2 dipole electromyography (EMG) (2 in study III) (Elekta Neuromag Ltd, Finland) at 600 Hz sampling rate. T1-weighted anatomical MRI scans (MP-RAGE) for cortical surface reconstruction models were obtained at a resolution of a 1 × 1 × 1mm with a 1.5-T MRI scanner (Siemens, Germany).

5.4 DATA PREPROCESSING
Classical trial rejection was used for trials with blinks, large saccades, or large mean amplitudes. Raw recording files were cleaned using temporal signal space separation with Maxfilter (Taulu and Kajola 2005; Taulu and Simola 2006). Independent component analysis based on Fieldtrip (Oostenveld et al., 2011) was used to remove eye, heartbeat, or strange spatial distribution and non-power-law distributed spectrum components in studies I and II.

5.5 BEHAVIORAL PERFORMANCE
In studies I and II target events that were responded to between 250 and 700 ms were considered as hits. Other events were considered as missed target events. Subjects were ordered into high and low capacity subjects according to their hit rates at 3 and 4 attentional loads.

In study III correct answers were considered as hits and incorrect answers as errors; trials with no answer were not analyzed.

5.6 SOURCE MODELING
MEG and EEG signals measured outside of the brain were used to estimate cortical activity using inverse modeling. Freesurfer was used to reconstruct individual skin, skull, and cortical surfaces (A. Dale and Sereno 1993; A. M. Dale et al., 1999; Desikan et al., 2006; Fischl, Sereno, Dale 1999; Fischl, Sereno, Tootell et al., 1999; Fischl and Dale 2000; Fischl et al., 2001; Fischl et al., 2002; Fischl et al., 2004; Segonne et al., 2004). Freesurfer was used to make individual anatomical parcellations which were further subdivided into 400 parcels by iteratively splitting the largest parcels. MNE software was used to create three layer boundary element models (BEM) for EEG and single layer BEM for MEG (Gramfort et al., 2014). MNE was used to co-localize the anatomical MRI and the functional MEG and EEG data and to create forward and inverse operators (Hämäläinen and Ilmoniemi 1994; M. S. Hamalainen and Sarvas 1989). MNE was used to create the source model with 7-mm dipole separation, of which a sub-selection of sources was automatically selected to optimize phase source reconstruction accuracy (Korhonen et al., 2014).
5.7 SIGNAL ANALYSIS

Source modeled data were Hilbert filtered with Morlet wavelets. Wavelet frequencies were distributed with a logarithmic distribution from 3 Hz to 90 Hz in study I and 3 to 120 Hz in studies II and III; wavelet cycles \( m = 5 \).

In studies I and III, amplitude of the analytical signal was used as the metric of cortical activity. In study II, the imaginary part of the complex phase locking value was used as a metric of 1:1 synchrony between cortical regions. Formula of cPLV:

\[
cPLV = \frac{1}{N} \sum_{n=1}^{N} e^{i(\theta_p(n) - \theta_q(n))}
\]

where \( N \) is the number of trials and \( \theta_p \) and \( \theta_q \) are the phases of the time series of parcels \( p \) and \( q \).

To exclude the direct effects of linear signal mixing (Nolte et al., 2004), we used as the interaction metric the absolute imaginary part (iPLV) of cPLV, \( iPLV = |\text{im}(cPLV)| \).

Cross-frequency interactions were studied with both phase amplitude coupling (PAC) and cross-frequency synchrony (CFS). Ratios of 1:2 to 1:10 were used. In case of the CFS phases of low and high frequencies were analyzed by multiplying the lower frequency’s phase by the \( m \) ratio, so that in one cycle of the lower frequency \( m \) roll-overs of phase happen.

We estimated \( n:m \) CFS for each pair of cortical parcels \( p \) and \( q \) and between pairs of low and high frequencies \( f_{\text{high}} \) and \( f_{\text{low}} \). We used the phase-locking value (PLV) to compute synchronization so that

\[
PLV_{p,q,n,m,f_{\text{low}},f_{\text{high}}} = \frac{1}{N} \left| \sum_{r} \exp[i \cdot (n \cdot \theta_p(r, f_{\text{low}}) - m \cdot \theta_q(r, f_{\text{high}}))] \right|
\]

where \( i \) is the imaginary unit, the integers \( n \) and \( m \) define the frequency ratio so that \( n f_{\text{high}} = m f_{\text{low}} \), \( N = r \), where \( r \) is the number of trials (Palva et al. 2005).

We estimated PAC by computing the 1:1 PLV between the phase of the slow oscillation and the phase of the amplitude envelope of the fast oscillation filtered at \( f_{\text{low}} \). PAC was defined as:

\[
PAC_{p,q,f_{\text{low}},f_{\text{high}}} = \frac{1}{N} \left| \sum_{r} \exp[i \cdot (\theta_p(r, f_{\text{low}}) - \theta_q^E(r, f_{\text{low}}, f_{\text{high}}))] \right|
\]

where \( \theta^E(f_{\text{low}}, f_{\text{high}}) \) is the phase of the filtered amplitude envelope \( E(f_{\text{low}}, f_{\text{high}}) \) that was obtained by filtering \( A(f_{\text{high}}) \) with the Morlet wavelet \( w(f_{\text{low}}) \):

\[
E(f_{\text{low}}, f_{\text{high}}) = A(f_{\text{high}}) \otimes w(f_{\text{low}}).
\]
5.8 Functional landmarks (for Study III)
To improve readability of flattened brains parcels were divided into putative functional groups using prior fMRI studies (Hansen et al., 2007; Kravitz et al., 2013; Tootell and Hadjikhani 2001; Yeo et al., 2011). Parcels spanning early (V1–V3), lateral-occipital (LO), location (dorsal), color (V4 and V8), and object information (ventral) areas were grouped. Putative functional networks of attention and executive control (dorsal attention, ventral attention and fronto-parietal networks) were co-localized with individual cortical surfaces (Yeo et al., 2011).

5.9 Statistical analysis
Behavioral performance differences were first estimated with ANOVA. Finding a significant result with ANOVA lead to using corrected t-tests to find which conditions were statistically different. Functional data was first analyzed in the frequency space (tasks I and II) and time-frequency space (task III) to find which frequencies and times had the most statistically significant results. These hotspots were then visualized in the anatomical dimension. In both cases fraction of significant results was used for visualization. This was done to avoid double dipping as the statistics was done only once but was visualized in two steps.

Alpha was kept at 0.05 in all statistical analyses, except for Study I’s Pearson’s $r$ which had alpha of 0.01. Performance contrasts were analyzed with t-tests (hit-miss or hit-error contrast). Load dependent differences were analyzed with Pearson’s correlation tests (study III) or Pearson’s randomization tests (studies I and II). Correlations with performance and functional brain data were analyzed with Pearson’s correlation tests. One-way ANOVA was used in Study III to estimate the influence of memorized feature on oscillation amplitudes. Two-way repeated measures ANOVA permutation test (Load x Task) was used to estimate how the tasks differed in Study II. Two-way mixed design ANOVA (Load x Capacity group) was used to estimate load-dependent differences between the capacity groups.

To correct for multiple comparisons alpha level of significant results were removed per each statistical test done (false discovery reduced correction).
6 RESULTS / SUMMARY OF PUBLICATIONS

6.1 BEHAVIORAL PERFORMANCE
In studies I and II hit rates decreased, and reaction times increased significantly with increasing target loads. Interestingly distractors did not hinder the performance at all. The hit rates were measured from 160 trials x 2 tasks x 4 loads = 1 280 total trials and reaction times from hit trials where the reaction time was between 250–700 ms.

In study III hit rates decreased and reaction times increased significantly with increasing target load. Shape memory task was the most difficult task, color and location tasks were the next most difficult and almost the same in difficulty, and the conjunction task was the easiest task. There was a lack of individual correlations between the tasks, which indicates that there are feature specific VWM capacity limits. The hit rates were measured from a total of 800 trials per single feature task and 1600 for the joint color-location task and defined as the proportion of correct responses from all trials.

6.2 STUDY I COMMON ATTENTIONAL LOAD EFFECTS
In both tasks of the multiple object tracking study at 8–20 Hz frequencies amplitudes correlated negatively with attentional load (Figure 1A, C). In both tasks the load dependent suppression was observed in left LPFC, left SM, left FEF and right visual regions (Figure 1B, D). A difference was observed in several areas between the tasks at 8–20 Hz; particularly interestingly right lateral and medial PFC had opposite direction of the correlation: positive correlation in Task2 and negative correlation in Task1. At 30–90 Hz frequencies amplitudes correlated positively with attentional load. In both tasks the 30–90 Hz amplitude strengthening was observed in visual regions, CO, TPJ, PPC and LPFC. The load dependent gamma activity was similar in both tasks, with the differences being that in Task1 the activity wider spread than in Task2 particularly in the left LPFC, and in T2 there was more activity in the right LPFC.
Figure 1: Study I results. Attentional load dependent oscillation amplitudes. The P values mean fraction of significant results out of all: in the frequency plots P means fraction of parcels active out of all parcels, in the anatomical plots fraction of frequencies out of indicated frequency selection. P+ is fraction of positive correlation results, P- fraction of negative correlation results. Left column: T1, right column: T2. A–D) Common load-dependent attentional amplitude effects (Pearson’s r, p < 0.01, corrected). E–H) Load-dependent attentional effects divided into low and high capacity subjects (Pearson’s r, p < 0.01, corrected). E–F) Colored solid lines for high-capacity subjects, dashed for low capacity. The gray line shows two-way mixed ANOVA interaction of Group x Load (p<0.05, corrected).

Labels: A, Anterior; m, middle; p, posterior; s, superior; i, inferior; C, central; D, dorsal; F, frontal; G, gyrus; J, junction; L, lateral; M, medial; O, occipital; P, parietal; S, sulcus; T, temporal; V, ventral; caS, calcarine sulcus; Ci, cingulated; FEF, frontal eye field (putative); IN, insula; IPS, intraparietal sulcus and transparietal; orb, orbital; orbSme, orbital sulcus and medial olfactory; som, somatomotor; PC, parietal cortex; PFC, prefrontal cortex; PPC, posterior parietal cortex (includes intraparietal sulcus [IPS] and superior parietal gyrus [sPG]); Vis, early visual areas (~V1–V4, blue circle).
6.3 STUDY I ATTENTIONAL LOAD EFFECTS DIFFERENCES BETWEEN CAPACITY GROUPS

Subjects were divided into high and low capacity subjects, leaving one subject out (the middle one) (see Methods – Behavioral performance). In both tasks oscillation amplitudes decreased at 7–12 Hz frequencies in both tasks and both capacity groups (Figure 1E-F). The activity was observed at alpha–beta frequencies (7–20 Hz) in both tasks and capacity groups in meOTS and medial visual areas (putatively V1/V2) (Figure 1G-H). There were several differences between the groups, but the most distinctive difference was that high capacity subjects had a strong 30–90 Hz activity increase with increasing load, whereas in low capacity subjects this was much less prominent. The 30–90 Hz load dependent amplitude increase was observed in high capacity subjects in widespread regions including lateral PFC, temporal, insular and visual areas, and importantly PPC and dorsal PFC which were not observed at all in the low capacity subjects. The amplitude increases were sparsely distributed in the low capacity subjects at 30–90 Hz and included visual, temporal and ventral PFC areas.

6.4 STUDY II COMMON ATTENTIONAL LOAD EFFECTS

To study which networks are common to high and low capacity subjects, first a two-way mixed ANOVA (Load x Capacity) was performed. Then Pearson’s permutation tests were performed for all subjects and separately for the high and low capacity groups. Those frequencies which showed both a load main effect and a significant positive correlation between synchrony and attentional load were chosen for closer inspection to study what connections were common for the subjects (Figure 2A).

In Task1 a main effect of load and positive correlation in 1:1 synchrony was observed at 3.7–4.5 Hz (Figure 2A). In Task2 4–5 Hz, and 70–90 Hz had a main effect of load and a positive correlation. Both tasks had main load effects at other frequencies but in most frequencies the high and low capacity groups do not have a positive correlation at the same frequency. The load dependent synchrony increase connections in Task1 around the 3.7–4.5 Hz were similar and thus were clustered at 3.7–4.5 Hz, showing widespread connectivity between multiple areas (Figure 2B). Largest hyper-edges connect left and right PFCs, visual areas, and PFC and visual areas.

In Task2 1:1 synchrony connections at low frequency were clustered at 3–5 Hz, showing connections mostly between visual areas and parietal areas (Figure 2B). In Task2 connections at high frequency were clustered at 70–120 Hz, with connections particularly between the right lateral PFC of the fronto-parietal network and left lateral PFC. There is also a strong connection between the right visual cortex and right dorsal PFC.

Load dependent cross-frequency coupling were observed to be stronger in Task2 than Task1 in both CFS and PAC (Figure 2H–I). Common cross frequency synchrony increases were observed in Task2 at 30–40 Hz coupled to 60–80 Hz in 1:2 ratio. Common phase amplitude coupling was observed at amplitude envelope of 35 and 45 Hz to phases of 18 and 23 Hz, and amplitude envelopes of 120 and 100 Hz to phase of 15 Hz.
Figure 2: Study II results. Attentional load-dependent synchrony. Connection density (K) is the fraction of significant connections out of all possible connections. A–B) Common load-dependent attentional 1:1 synchrony effects (Pearson’s r randomization test p<0.05, corrected). C–F) Load-dependent attentional 1:1 synchrony effects divided by low and high capacity subjects (Pearson’s r randomization test p<0.05, corrected). A) Two-way ANOVA (Load x Task) permutation test (p<0.05, corrected, above threshold). C, E) Solid lines for high-capacity subjects, dashed for low-capacity subjects. The lines/dots above are results of two-way mixed measures ANOVA (Load x Capacity group) permutation test (p<0.05, corrected, above threshold). D–F) Note that High and Low texts refer to the high and low capacity subjects grouping. G) Anatomical map with parcels colored according to the Yeo7 parcellation (Yeo et al., 2011) visual (Vis), limbic (Lim), default (Def), somatomotor (SM), dorsal attention network (DAN), ventral attention network (VAN), frontoparietal network (FPN) and non-co-localized (Mix) parcels. H–I) Load-dependent cross-frequency coupling measures (Pearson’s randomization test p<0.05). Values are colored when connection density was > 99.9% compared to shuffled data. The green squares indicate significant differences between the high and low capacity subjects. Labels as in Figure 1.

6.5 STUDY II ATTENTIONAL LOAD EFFECT DIFFERENCES BETWEEN CAPACITY GROUPS

Mixed two-way ANOVA (Load x Capacity) interaction effect was used to see what 1:1 synchrony load dependent connectivity differences were between the groups. In Task1 there were interaction effects at 6 Hz, 15–16 Hz, and 30–35 Hz (Figure 2C). In Task2 there were interaction effects at 10 Hz, 13 Hz, and 120 Hz (Figure 2E). The load and capacity interactions were at smaller frequency band than what the connectivity similarity clustering gave. In Task1 the 6 Hz interaction effect is not particularly interesting as the connection densities there are below the threshold and are thus suspect.

In Task1 the interaction effect around high-alpha to low beta frequency was due to an increase in load dependent 1:1 synchrony observed in low capacity subjects (Figure 2C). The connections were clustered at 13–18 Hz, showing connections especially between the frontal areas, frontal- and visual areas, and left motor-areas and left parietal association areas (Figure 2D). In Task1 the interaction effect around low gamma was due to an increase in load dependent synchrony observed in high capacity subjects. The connections of high capacity subjects were clustered at 30–40 Hz, with connections bilaterally between areas near temporal junctions, left temporal junction and left PFC, and visual areas and right somatomotor network areas.

In Task2 the interaction effect around mid-alpha was due to an increase in load dependent 1:1 synchrony observed in high capacity subjects (Figure 2E). The connections were clustered at 7–15 Hz, with connections bilaterally between PFC areas, and to a lesser degree also between higher visual and PFC areas (Figure 2E). In Task2 the interaction effect around high alpha was due to an increase in load dependent synchrony observed in low capacity subjects. The connections were clustered at 12–13 Hz, with widespread connections between many areas, particularly many between the left visual areas and almost all brain areas. In Task2 the interaction effect at high gamma was due to an increase in load dependent synchrony observed in high capacity subjects.
The connections were clustered at 72–120 Hz, with connections mostly between the right PFC and widespread areas bilaterally including mostly visual, parietal and temporal areas.

Load dependent cross frequency differences were seen more in Task2 than Task1 (Figure 2H–I). In Task1 high capacity subjects had more phase amplitude coupling at amplitude of 90–120 Hz coupled to phase of 24–30 Hz. In Task2 PAC was greater in high capacity subjects at high gamma frequency coupled to beta frequencies (70–120 Hz amplitude envelopes coupled to 15–30 Hz phase).

6.6 STUDY III DIFFERENCES BETWEEN LOADS 2 AND 4

The difference between attentional loads at 2 and 4 objects were tested with t-test of baseline corrected data. In the attend on Shape condition there was a late 40–120 Hz (gamma) amplitude increase, located mostly in frontal areas (Figure 3A). In the attend on color condition there was an early 25–120 Hz (beta and gamma) amplitude increase that was localized in early visual areas and PFC and a decrease in the parietal and temporal areas in the gamma frequency, with the beta band having also decreases in the frontal areas (Figure 3B). In the attend on location condition there was a sustained early and late retention period 20–35 Hz (beta) amplitude increase in early visual areas with a decrease in parietal, temporal and frontal areas (Figure 3C). In the attend to color and location (conjunction) condition there was a sustained 20–70 Hz (beta and gamma) load dependent amplitude increase and a late (0.8–1.5 s) amplitude decrease at 3–5 Hz and 40 Hz (Figure 3D). The gamma increase was widespread but the strongest effects were localized at the left temporal regions and right PFC. The beta band amplitude changes were also widespread with the strongest effects localized bilaterally to early visual areas, and to the right medial parietal cortex.
Figure 3: Study III results. A–C) Feature specific memory load oscillation amplitude effects. Warm colors mean stronger amplitudes in 4 objects load condition than in 2 objects load condition. D) Same as A–C but for color-location conjunction. Note that the different features are organized by columns. E) Color-location conjunction task has stronger amplitudes at gamma frequencies, and weaker amplitudes at lower frequencies than the color and location feature tasks separately. F–G)
Correlations with load-dependent amplitude change and hit rate between loads 2 and 4. Warm colors mean positive correlation with amplitudes and behavioral accuracy, cold colors a negative correlation. H) Anatomical map with the different visual regions (colored) and functional regions (gray scale). The functional regions as in Figure 2G, except that only three are shown. Note that the time-frequency plots have a different color scales, except A and B. All of the flattened pictures have the same color scale.

6.7 STUDY III COMPARISON BETWEEN JOINT AND SEPARATE COLOR AND LOCATION ATTENTION
To study how binding of two features affects brain activity compared to separately attending on single features, we compared the color and location conditions and their conjunction with t-tests. Warm colors in the figure mean greater amplitude in the conjunction condition than in the mean of color and location conditions. Both loads 2 and 4 were used in the analysis. There was a sustained amplitude difference at 40–120 Hz (gamma), around 20 Hz (beta), and 5–10 Hz (alpha) (Figure 3E). At the gamma band the conjunction condition had greater amplitude, at beta and alpha both greater and lower amplitudes than the separate conditions. The gamma difference was mostly observed in the left hemisphere in parietal, temporal, somato-motor, and prefrontal areas. The beta band increases were observed in left occipito-temporal and bilateral PFC, and decreases in occipital, parietal and central sulcus areas.

6.8 STUDY III LOAD CORRELATES
To study the relationship between performance and oscillation amplitudes we correlated hit rate at load 2-4 and amplitudes at load 4-2, giving a positive correlation a meaning of less decrease in HR with increasing amplitude strength. In the attend to Shape condition there was a sustained 30–120 Hz and wide spread positive correlation (Figure 3F). There was some transient negative correlation at 45–60 Hz (low gamma) in the V1–V3 and dorsal parietal areas during 1–1.5 s of the retention period. In the attend to Color condition there was a transient positive correlation in the early retention period (0.6–0.8 s) at 16–30 Hz (beta) and 80–120 Hz (gamma), which was localized to a large extent to the right hemisphere at the gamma frequency (Figure 3G). There was a widespread negative correlation in the 16–40 Hz during most of the retention period (0.8–2 s), which was localized especially in the ventral visual areas.
7 DISCUSSION

We used source-modeled MEG/EEG to study the functional role of cortical oscillations in attending visually to multiple objects and retaining different visual features in memory. We found that in multiple object tracking (MOT) tasks alpha amplitudes are suppressed as load increases, but that inter-areal alpha synchronization is increased when there are distractors to be ignored. Local amplitudes and inter-areal synchrony was increased at gamma frequencies particularly in subjects who performed well in the MOT task. The local amplitude differences of multi-object attention between high and low capacity subjects were observed in frontal and parietal regions at beta and gamma frequencies. Inter-areal synchrony differences between high and low capacity subjects were observed at alpha, beta and gamma frequencies, with the two groups showing distinct connectivity patterns. We observed phase-amplitude coupling (PAC) specifically in high-capacity subjects. In the visual working memory (VWM) task we found distinct load-dependent differences for retaining color, location, and shape features in both cortical region activation patterns, frequencies observed and timing of the activations. Increased gamma-band amplitudes were observed during subjects attending to color and location both compared to separate feature attention. These VWM results suggest that gamma oscillations underlie retention of visual representations and that gamma oscillations reflects integration of those representations. The MOT results suggest that particularly gamma frequency amplitude activity and alpha/beta and gamma frequency synchrony and PAC set low- and high-capacity subjects apart, with high capacity subjects having more gamma activity.

7.1 ALPHA AND BETA AMPLITUDES ARE DECREASED, AND GAMMA AMPLITUDES ARE INCREASED WITH ATTENTIONAL LOAD

In Study I MOT tasks, with and without distractors, load-dependent alpha- and beta-band oscillation amplitudes were decreased, and load-dependent gamma-band oscillation amplitudes were increased (Figure 1A–D). The load-dependent gamma-band amplitude increases were observed in LPFC, PPC, CO and visual regions. In prior fMRI studies activity in PPC and prefrontal areas have been found to correlate with multi-object attention (Corbetta and Shulman 2002; Kastner and Ungerleider 2000). Gamma-band amplitudes have been observed to strengthen in many attentional tasks (Gruber et al., 1999; Kaiser et al., 2006; Muller and Keil 2004; Siegel et al., 2008; Wyart and Tallon-Baudry 2008). The strengthened gamma-band activity is in line with the prior studies except that the activity was found in more areas than in the fMRI studies. MEG and EEG studies complement fMRI studies particularly when using source modeling. In most of the attention studies sensor level analysis was used, so the location of the load-dependent activity was not well characterized.

Alpha-band amplitude increase is often considered as inhibiting task-irrelevant areas especially in early visual areas (Klimesch et al., 2007; Pfurtscheller 2003; Ray and Cole 1985; Sauseng et al., 2009), though this does not always hold especially in higher or frontal areas (Haegens et al., 2011; Mo et al., 2011). The decrease of alpha amplitude with increasing load is in line with the view that
alpha amplitudes have an active inhibitory role (Jensen and Mazaheri 2010). The current study characterized source-modeled multi-object attention with oscillatory activity, which has been studied but little before.

7.2 Load-dependent gamma-frequency oscillatory amplitudes predict attentional capacity
In Study I subjects were divided into high and low capacity subjects according to their hit rates at high attentional loads. High-capacity subjects were observed to have much stronger load-dependent gamma band amplitudes than low-capacity subjects (Figure 1E–H). As the stimuli were the same for both capacity groups, this suggests that the gamma amplitude reflects objects maintained in attention. This is in line with EEG activity plateauing when capacity is reached (Vogel and Machizawa 2004). Also, a similar dependence with gamma and capacity was observed in a VWM study (S. Palva et al., 2011). These results suggest common mechanisms for visual attention and VWM (Awh and Jonides 2001). Ability to control attention has been suggested to explain the difference between high and low WM capacity individuals (Engle 2018), which would indicate that the common mechanism for visual attention and VWM would be attention’s mechanisms.

The load-dependently strengthened gamma amplitudes were observed in LPFC, PPC, and IPS in Study I. Prior fMRI studies have revealed correlations with multi-object attention in PPC and PFC (Corbetta and Shulman 2002; Kastner and Ungerleider 2000), suggesting that Study I’s high capacity subjects could engage these areas important for attention with greater efficiency with gamma frequency oscillations being the mechanism underlying the capacity difference. Our results support the idea that gamma oscillations are critical for perception (Beauchamp et al., 2012).

7.3 Low- and high-capacity subjects have distinct large-scale synchrony networks
In Study II we observed load-dependent differences in the spectral and anatomical patterns of large-scale synchrony. In Task2 where distractors were visible greater load-dependent gamma was observed than in Task1 where there were no distractors (Figure 2C–F). In Task1 the most robust difference between capacity groups was at beta and low-gamma frequencies. Both beta and gamma band synchronization have been observed to strengthen by attention in animal studies (Buschman and Miller 2007; Womelsdorf et al., 2006; Womelsdorf and Fries 2006). Also attention in a serial task increased beta-band synchronization between frontal, parietal and temporal regions (Gross et al., 2004), implying that the low-capacity subjects might be observing the targets in a more serial fashion than the high-capacity subjects.

In Task2 differences in the large-scale alpha-band synchrony were observed between low- and high-capacity subjects, where low-capacity subjects’ network was more between the early visual areas, whereas high-capacity subjects’ network had more connections between the frontoparietal areas. There are many studies where frontoparietal connectivity is implicated in attention (e.g. (Corbetta and Shulman 2002; Ekman et al., 2016; Fuster 2000; Fuster 2001; Kastner and
Ungerleider 2000), so it might be that alpha synchrony between frontoparietal areas sets high- and low-capacity subjects apart in a task requiring ignoring distractors. The observed load-dependent increase in alpha synchrony is evidence against a simplistic view that alpha is merely inhibitory (Lozano-Soldevilla et al., 2014; Lozano-Soldevilla 2018; S. Palva and Palva 2007). We did not ask what strategy the subjects used, but it might be that different strategies could explain some of the behavioral and brain activity differences between the groups, like in a prior fMRI study (Merkel et al., 2015). It would be interesting to have subjects explicitly use different strategies and see how this would affect behavior and network activity.

7.4 Beta to gamma phase-amplitude coupling is observed in high-capacity subjects
In Study II we observed significant load-dependent beta phase to gamma amplitude coupling (PAC) in high-capacity subjects but not in low-capacity subjects in both tasks (Figure 3H–I). In Task2 cross-frequency synchrony (CFS) was observed but not in Task1. The CFS was observed in both low- and high-capacity subjects. In a prior spatial attention task study theta and gamma CFS was observed to be enhanced by attention (Sauseng et al., 2008). In Study II beta and gamma CFS was observed. In a prior VWM task CFS between theta and alpha to beta and gamma was observed (Siebenhühner et al., 2016). In VWM tasks PAC between theta and gamma (Polania et al., 2012) and high alpha and gamma (Barnes et al., 2016) was observed. The higher frequency PAC coupling we observe in Study II might be due to task differences between the prior studies and Study II. We observed large differences in synchrony patterns between Task1 and Task2, so it might not be too surprising to see differences in the PAC of Study II to the VWM studies.

We observed significant activity in oscillatory activity using amplitude and synchrony metrics. Cross-frequency coupling could well be a mechanism for coordinating the different neuronal large-scale activities (J. M. Palva and Palva 2017). The greater gamma-band amplitudes observed in high capacity subjects in Study I might at least partially be driven by beta. It would be interesting to test explicitly in an attentional study if sequential style of attention caused increased 1:1 beta synchrony and concurrent style of attention caused 1:n beta to gamma phase-amplitude coupling.

7.5 Behavior and retention time beta and gamma amplitudes indicate feature-specific VWM
In Study III we found feature-specific memory-load dependent oscillation amplitudes to have distinct frequency and cortical activation patterns (Figure 3A–D). Gamma-band oscillations have been found to be increased during VWM maintenance (Jokisch and Jensen 2007; Medendorp et al., 2007; Morgan et al., 2011; S. Palva et al., 2011; Roux et al., 2012; Sauseng et al., 2009). We found that load-dependent gamma was increased in the attend to shape and color feature tasks. The most difficult task feature, attend to shape, had a distinct late retention period gamma amplitude increase particularly in frontal regions. Attend to color task showed an early beta and gamma amplitude increase in early visual and PFC areas, with beta and gamma amplitude decreases particularly in the parietal and temporal areas. Attend to location task showed a sustained beta
amplitude increase in early visual regions and decreases in parietal, temporal and frontal areas. We also observed that strong gamma-band load effects predicted behavioral smaller load-dependent hit rate declines, particularly in the difficult shape condition. Our results indicate that gamma-amplitude activity might underlie the retention of shape and color VWM features, but not the spatial feature. Behaviorally there was a lack of individual correlations between the tasks. The behavioral and functional results indicate feature-specific VWM that rely on beta- and gamma oscillation amplitude activity. One of the strengths of Study III was that multiple tasks were done. If we had done only one of the experiments one would have a skewed view of load-dependent VWM amplitude effects.

Alpha-band oscillations have been found to be strengthened during WM (Jensen et al., 2002; Nenert et al., 2012; S. Palva et al., 2011). We did not find feature specific load-dependent alpha-band amplitude differences, suggesting that alpha-band oscillations might serve a common purpose during VWM.

7.6 **GAMMA-BAND ACTIVITY IS INCREASED DURING BINDING OF VISUAL FEATURES**

We found increased gamma-band activity during VWM retention period when subjects retained both color and location compared to when they retained color or location separately (Figure 3E). Gamma-band activity has been suggested to be related to perceptual integration and maintenance of VWM (Magen et al., 2009; Polanía et al., 2012; Tallon-Baudry et al., 1998), which our results support. VWM activity is widespread in the brain (D’Esposito and Postle 2015; Larocque et al., 2014), with object representations being held in visual regions according to fMRI studies (Harrison and Tong 2009; Riggall and Postle 2012), while attentional and executive functions are associated with frontoparietal regions (Fuster 2000; Fuster 2001; Kastner and Ungerleider 2000). The increased gamma amplitudes associated with increased binding demands we observed were located mostly to left hemisphere’s parietal, temporal, somato-motor, and prefrontal areas, suggesting that gamma oscillations support distributed feature processing (Jensen et al., 2007; Singer 1999; Tallon-Baudry and Bertrand 1999).

8 **CONCLUSIONS**

Our results suggest a critical and task-specific flexible role for gamma-band activity that supports good perceptual performance in tasks requiring attention. Gamma-band activity was associated with high performance in multi-object attention and binding of visual features in visual working memory retention. Alpha activity was found to have different roles in local and large-scales in multi-object attention. The results indicate an inhibitory role for local alpha amplitude modulations, whereas the large-scale alpha synchrony actively supports multi-object attention.
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10 References


40


11 PUBLICATIONS
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