Time and Numbers, or the when and where of attentional processing

A psychophysiological approach using the SSVEP

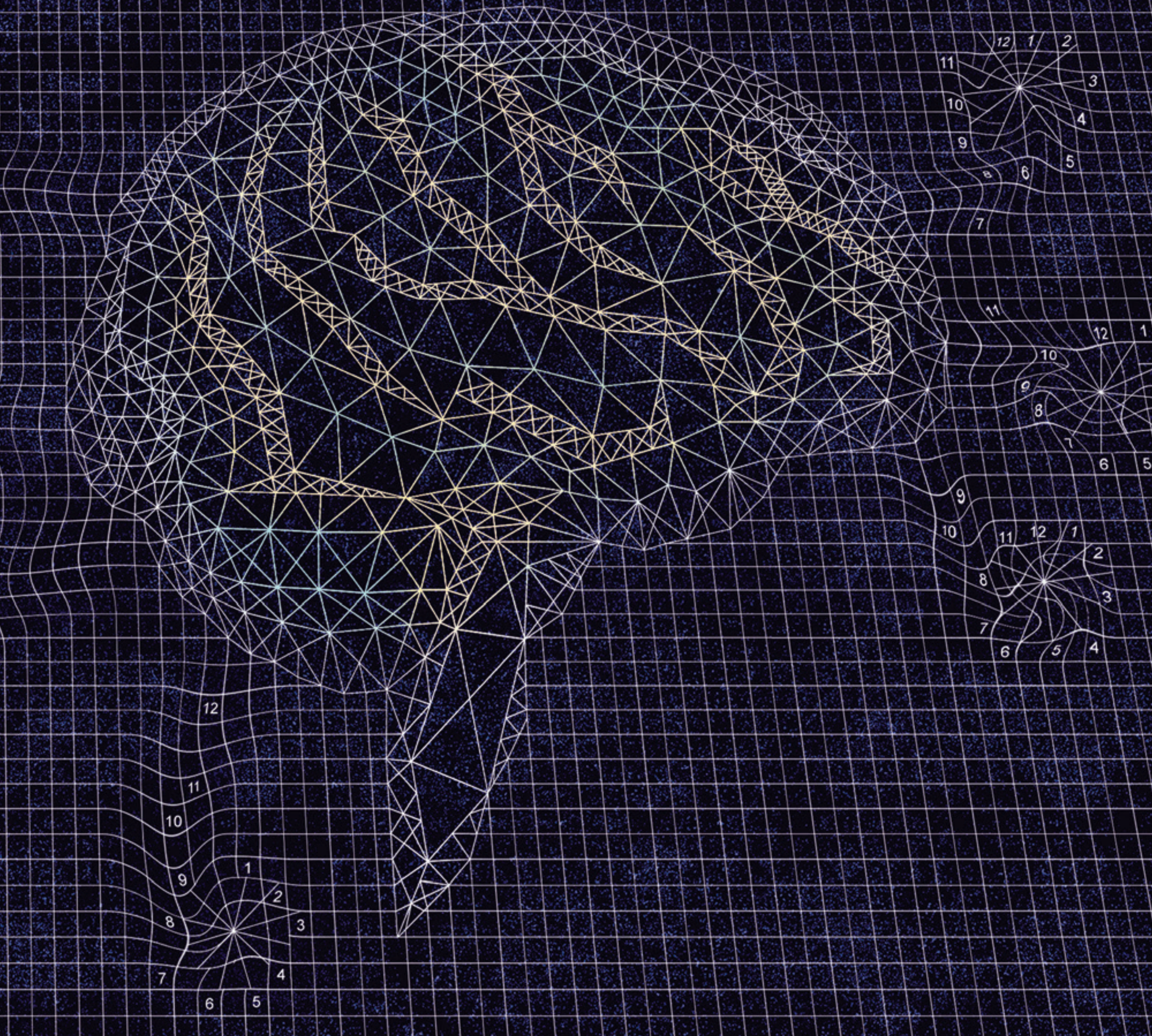
Mora Cortes, A.

Publication date
2018

Document Version
Final published version

License
Other

Time and Numbers, or the *when* and *where* of attentional processing: A psychophysiological approach using the SSVEP



Anderson Mora Cortes

Time and Numbers, or the when and where of attentional processing: A psychophysiological approach using the SSVEP

Anderson Mora Cortes

The research reported in this doctoral thesis was supported by the Departamento Administrativo de Ciencia, Tecnología e Innovación, Colciencias, Colombia, under grant number 529/2011.

ISBN: 978-94-028-1040-0
Cover designed by Floortje Bouwkamp & Anderson Mora Cortes
Printed by Ipskamp Printing B.V., Enschede

Time and Numbers, or the when and where of attentional processing: A psychophysiological approach using the SSVEP

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. ir. K.I.J. Maex
ten overstaan van een door het College voor Promoties ingestelde commissie,
in het openbaar te verdedigen in de Agnietenkapel
op dinsdag 29 mei 2018, te 12:00 uur

door

Anderson Mora Cortes
geboren te Bogotá, Colombia

Promotiecommissie:

Promotores:	Prof. dr. K.R. Ridderinkhof	Universiteit van Amsterdam
	Prof. dr. M. M. Van Hulle	KU Leuven
Copromotor:	Dr. M. S. Cohen	Radboud Universiteit Nijmegen
Overige leden:	Dr. J. Duprez	Radboud Universiteit Nijmegen
	Prof. dr. B.U. Forstmann	Universiteit van Amsterdam
	Prof. dr. C.C. van Leeuwen	KU Leuven
	Prof. dr. M.W. van der Molen	Universiteit van Amsterdam
	Dr. F. van Opstal	Universiteit van Amsterdam
	Prof. dr. W. Schaeken	KU Leuven
	Dr. H.A. Slagter	Universiteit van Amsterdam

Faculteit der Maatschappij- en Gedragswetenschappen

This thesis was prepared within the partnership between the University of Amsterdam and KU Leuven with the purpose of obtaining a joint doctorate degree. The thesis was prepared in the Faculty of Social and Behavioural Sciences at the University of Amsterdam and in the Laboratory for Neuro - and Psychophysiology, Doctoral School Biomedical Sciences at the KU Leuven.

Dit proefschrift is tot stand gekomen binnen een samenwerkingsverband tussen de Universiteit van Amsterdam en de KU Leuven met als doel het behalen van een gezamenlijk doctoraat. Het proefschrift is voorbereid in de Faculteit der Maatschappij- en Gedragswetenschappen van de Universiteit van Amsterdam en de Laboratory for Neuro - and Psychophysiology, Doctoraatsprogramma Biomedische Wetenschappen van KU Leuven.

KU Leuven
Biomedical Sciences Group
Faculty of Medicine
Department of Cognitive and Molecular Neuroscience

KU LEUVEN
DOCTORAL SCHOOL
BIOMEDICAL SCIENCES

Time and Numbers, or the when and where of attentional processing: A psychophysiological approach using the SSVEP

Anderson Mora Cortes

Dissertation presented in partial fulfillment of the requirements for the degree of Doctor in Biomedical Sciences

Jury:

Promoter: Marc M. Van Hulle
K. Richard Ridderinkhof
Co-promoter: Michael S. Cohen
Chair: Prof. dr. Agneta Fisher
Secretary: Prof. dr. K.R. Ridderinkhof
Jury members: Dr. J. Duprez
Prof. dr. B.U. Forstmann
Prof. dr. C.C. van Leeuwen
Prof. dr. M.W. van der Molen
Dr. F. van Opstal
Prof. dr. W. Schaeken
Dr. H.A. Slagter

May 2018

CONTENTS

LIST OF ABBREVIATIONS

AAC	Alternative and augmentative communication
AAL	Ambient assisted living
ALS	Amyotrophic lateral sclerosis
ANOVA	Analysis of variance
BCIs	Brain-Computer Interfaces
CNV	Contingent negative variation
c-VEP	Code modulated visual evoked potential
EEG	Electroencephalogram
ERD	Event-related desynchronization
ERP	Event-related potentials
ERS	Event-related synchronization
FFT	Fast Fourier transform
fMRI	Functional magnetic resonance imaging
fNIRS	Functional near infrared spectroscopy
f-VEP	Frequency visual evoked potential
FWHM	Full width at half-maximum
IPS	Intraparietal sulcus
ISI	Inter-stimulus intervals
ITPC	Intertrial phase coherence
ITR	Information transfer rate
MEG	Magnetoencephalography
MI	Motor imagery
MNL	Mental number line
OCM	Output character per minute
PCT	Polarity correspondence theory
PET	Positron emission tomography
RSVP	Rapid serial visual presentation
RESS	Rhythmic entrainment source separation
RTs	Reaction times
SNARC	Spatial-Numerical Association of Response Codes
SNR	Signal-to-noise ratio
SOA	Stimuli-onset asynchrony
SRC	Stimulus response compatibility
SSVEP	Steady-state visual evoked potential
SVM	Support vector machine
t-VEP	Transient visual evoked potentials

Chapter 1

INTRODUCTION

The world around us is constantly changing and our senses are bombarded with more information than our brains can ever handle. To deal with the overload, our brain filters out information with respect to the requirements posed by the environment and our own goals at any given moment in time. *Attention* is the term used to describe which aspect of the incoming sensory information our brain considers relevant for guiding behavior. Attentional processing not only prevents the aforementioned overload but also helps us to keep track of possible changes in the environment so that we can anticipate and adjust our behavior. Nevertheless, directing attention to relevant information does not happen always in the same way and within the same brain networks as, depending on the task, our brain switches between being an interpreter of the sensory information and a predictor of the upcoming stimuli. For example, imagine that you are driving a car in a street with just two lanes, then you reach an intersection with three traffic lights, each one controlling traffic in three different directions: when the traffic lights turn red you need to *pay* attention to the traffic light controlling the direction you need to follow to turn back to green. If you are waiting to turn to the right, you will probably direct your attention to the traffic light controlling this direction while ignoring the other two traffic lights. But if the three lights are placed next to each other, you will probably see the three lights at the same time. Now you need to focus on the light that is more relevant for you while ignoring the other two although they are still “visible” to you. And once the light you are attending to turns amber you can *predict* the moment when it turns green so you can continue driving.

In this example our brain selects which stimuli are relevant to avoid getting involved in a traffic accident. And, even though all the lights are within your visual field, and you are attending selectively to one particular light, you covertly (meaning without moving your gaze from the relevant light) can see when the other traffic lights turn from red to amber. This division of your spatial attention between relevant and irrelevant lights has an additional benefit to the current task. On the one hand, selectively attending to the relevant traffic light creates a framework for improving our perception of the relevant aspects (the traffic light relevant for you) and demoting those that are irrelevant (all the other traffic lights). On the other hand, the spatial allocation of attention to one particular area of the visual field has predictive value of our next action: when the light for going straight changes from red to amber, our brain will use this cue to anticipate the moment when the light for turning right becomes green, in this way enhancing our driving efficiency.

By timely performing these complex computations, our behavior keeps pace with the changing context and provides us with clues how our brain is dealing with the overwhelming amount of relevant and irrelevant information in our environment. And to better understand how each of these processes occurs at a biological level is one of the main goals of cognitive neuroscience. In the present thesis, I investigated how spatial attention can be driven by numerical cues. And I also extended the use of a very interesting technique, frequently used in electrophysiology to study temporal and spatial attention, and evaluated its reliability in understanding the neural mechanisms underlying these processes.

Selective attention

What our brain does to properly direct our behavior according to each particular situation has been termed *attention*. However, attention involves a broad range of different mechanisms controlling different processes. There are different aspects to attention as different cognitive abilities and different brain networks could be involved. Thus, the processes that occur when our brain filters out irrelevant information and voluntarily attends to relevant information have been named selective attention (Desimone & Duncan, 1995). Although selective attention frames the most relevant information needed to guide our current behavior, this selection is biased and limited by the available cognitive resources restricting locations of attention selection in time as well as in space (Wolfe, 2014). While the former describes attentional variations over time, and also the effect in performance when attending to different points in time (Nobre, 2001), the latter enhances the processing of information at the attended location. Nonetheless, spatial attention also describes a temporal component since it has been reported that attention monitors between the spatially attended and unattended locations within milliseconds providing spatiotemporal benefits to spatial attention processing for a flexible adjustment according to changes in the environment (Jia, Liu, Fang, & Luo, 2017).

Interestingly, the networks involved in temporal attention partially overlap with those involved in spatially orienting attention (Coull & Nobre, 1998). However, based on the conditions that drive attention to a particular spot in space or temporal conditions requested to perform a current task, differential and specific mechanisms between temporal and spatial attending could be activated (Coull & Nobre, 1998). Nonetheless, how some particular aspects involved in temporal (e.g., attention modulation effects of temporal expectations) and spatial (e.g. effect of numbers on spatial attention) attention work remains unclear, due to a lack of physiological evidence to fully understand the temporal and spatial aspects of attention.

In the present thesis I studied temporal and spatial attention using the steady-state visual evoked potential (SSVEP). Regarding temporal attention, I evaluated the feasibility of the SSVEP technique to extend our knowledge about temporal expectations as it could improve our understanding and use of temporal cues to guide behavior in clinical disorders such as Parkinson's (Rochester et al., 2005) and Schizophrenia (Silberstein, Line, Pipingas, Copolov, & Harris, 2000). I have also been using SSVEP to study the role of numbers in spatial attention, as it could extend our knowledge about the mental representation of numbers in space (Dehaene, Bossini, & Giraux, 1993), under two specific circumstances: when numbers are relevant (Fias, Lauwereyns, & Lammertyn, 2001) and when they are irrelevant to the task (Fischer, Castel, Dodd, & Pratt, 2003).

In this introduction I will describe temporal attention, and the role of temporal expectation and its effects on behavior; then, I will describe the neural mechanisms underlying the processing of temporal expectations that influence perceptual and motor performance. Thereafter, I will describe some of the theories describing mental representation of numbers and how this representation affects behavioral performance and its relation with spatial attention. Next, I will describe the neural mechanisms that support the mental representation of numbers. Finally, I will describe the SSVEP and will introduce the rhythmic entrainment source separation (RESS) spatial filter used in this thesis to perform all EEG analyses. Therefore, this introduction provides a background on the use of SSVEP in the two specific aspects of attentional processing for the studies conducted to complete this thesis.

Time in attentional processing

Different types of cues that induce temporal expectations have shown to improve not only reaction times (RT) but also perceptual detection and discrimination. However, there are still open issues regarding the mechanisms of temporal expectations that benefit behavioral performance, e.g., why a particular cue that induces temporal expectations enhances perceptual processing in a particular task, but this enhancement is different in a similar task when using different types of cues to induce temporal expectations. It is important to extend our knowledge about the role of time in attentional processing as it could shed light on the mechanisms underlying time processing, attentional processing and the interaction between them, as they improve our behavioral performance in different contexts. Unraveling the role of time is relevant not only for fundamental science but also for clinical practice when applying temporal cues in the treatment of impaired ageing and some clinical disorders. Because there is no evidence of the use of SSVEP to study temporal attention, in this thesis I implemented the SSVEP in the context of temporal attention (**Chapter 3**). Thus, in the following paragraphs, I will describe the general background of time processing in attention, temporal expectations and the underlying mechanisms that describe the effects of time on behavior.

Time could affect attentional processing in different ways depending on how time is related to the task. If performing a task requires paying attention to the same stimulus for a prolonged period of time, performance will inevitably decrease because alertness will decline (Warm, Dember, & Hancock, 1996). If detecting the one or the other of two consecutive stimuli depends on the time interval between them, the length of that interval will determine whether one or both stimuli are detected (e.g., Attentional blink-AB-; Raymond, Shapiro, & Arnell, 1992), but if time is related to the onset of the upcoming stimulus it could help to predict the presentation of the upcoming stimulus (Coull & Nobre, 1998; Nobre & Rohenkohl, 2014). The role of the temporal dimension clearly transforms the concept of attention from the static concept of *paying attention* to an elegant, dynamic and flexible process capable of organizing information dynamically according to the conditions and restrictions defined by the temporal dimension itself. Thus, following the idea that time induces expectations regarding when a forthcoming stimuli will appear, I will focus on temporal orienting and how expectations have an effect on behavior.

In several of the tasks performed in daily life people use different types of temporal cues to anticipate the timing of an event. It could be according to the bus schedule while waiting for the next bus, according to the red light to turn green when driving, or according to a previously scheduled meeting time when trying to be there on time. In Experimental psychology, the study of temporal orienting, and how time manipulation provides a benefit in response times, goes back to 1887 as described by Correa (2010). Nobre & Rohenkohl (2014) reported that it was Wundt (1874/1904) who first reported improvements in RTs when a using warning signal that predicts an upcoming target after a constant and predictable interval. Then, by manipulating the regularity of the time interval between the warning signal and the event, the so-called foreperiods, Woodrow (1914) showed that performance of the participants improved in trials when the interval was constant and predictable compared to trials with variable and unpredictable intervals. Woodrow also reported that certainty about the foreperiods improves the degree of preparation for response overtime.

The benefits of using temporal cues were later shown to go beyond speeding motor responses and were tested in the auditory (Egan, Greenberg, & Schulman, 1961; Zahn & Rosenthal, 1966) and visual domain (Lasley & Cohn, 1981; Lowe, 1967; Westheimer & Ley, 1996). Coull and Nobre (1998) adapted the Posner, Snyder, & Davidson (1980) covert spatial task to describe the different neural systems involved in guiding spatial versus temporal expectations. Since then, the study field of temporal attention has grown (Nobre, 2010; Nobre & Rohenkohl, 2014) as well as the type of cues used to induce temporal expectations besides the foreperiods mentioned above.

Inducing temporal expectations

In a typical temporal attention task, a temporal cue explicitly indicates whether the onset of the upcoming task-relevant stimulus will appear after a short or long time interval where the short cue interval is associated with an early onset of the stimuli and the long cue interval is associated with a late onset of the stimulus. When the target is presented after the cue, participants should respond as fast and accurate as possible. And typically, performance reveals faster RTs for targets presented after a valid and short cue (e.g., cue for 400 ms and target present at 400 ms) as compared with targets presented after a long (e.g., cue for 1200 ms and target present at 1200 ms) or invalid cue (e.g., cue for 1200 ms and target present at 400 ms). This type of temporal cues are predictive since they provide temporal information regarding the time interval after which a target stimulus appears (e.g., short: 400 or long: 1200 ms), and previous studies have provided evidence about the benefits in performance when using predictive cues (Davranche, Nazarian, Vidal, & Coull, 2011; Griffin, Miniussi, & Nobre, 2001, 2002; Miniussi, Wilding, Coull, & Nobre, 1999).

Similarly, in an analogous way to the use of cues in spatial attention, instructive cues induce temporal expectations and provide information to participants when (instead of where) to pay attention to the likely presentation of the next stimuli (Coull, Davranche, Nazarian, & Vidal, 2013; Coull & Nobre, 1998; Lampar & Lange, 2011). The main difference between predictive and instructive cues is that the former predict the time interval when a target appears while the latter provides information about the specific time point when a stimulus (either target or nontarget) will be presented. Similar temporal expectancies inducing effects have been reported using rhythmic stimulation, where the stimuli-onset asynchrony (SOA) could be either constant/regular or jittered/irregular between the stream of presented stimuli, (Cravo, Rohenkohl, Wyart, & Nobre, 2013; Jones, Moynihan, MacKenzie, & Puente, 2002; Rohenkohl, Coull, & Nobre, 2011; Rohenkohl, Cravo, Wyart, & Nobre, 2012; Rohenkohl & Nobre, 2011); manipulating the hazard rates where the conditional probability of occurrence of the next target at a specific time is defined by the fact that it has not yet occurred (Janssen & Shadlen, 2005; Vangkilde, Coull, & Bundesen, 2012; Vangkilde, Petersen, & Bundesen, 2013); or by manipulating the regularity or interstimulus interval (ISI) between stimuli in a task, where the time between the offset of the last stimulus and the onset of the upcoming stimulus could be either constant or variable (Jepma, Wagenmakers, & Nieuwenhuis, 2012; Los & Agter, 2005; Los, Knol, & Boers, 2001).

Temporal expectations have shown to improve behavioral performance speeding reaction times (e.g., Doherty, Rao, Mesulam, & Nobre, 2005) and perceptual sensitivity (e.g., Correa, Lupiáñez, & Tudela, 2005). Supporting these effects, several studies have reported anticipatory modulation of neural activity associated with temporal expectations that enhance perceptual processing of events happening at expected times both in the visual (Mathewson et al., 2012; Mathewson, Fabiani, Monica, Beck, & Lleras, 2010; Praamstra, Dimitrios, Kwok, & Oostenveld, 2006; Rohenkohl & Nobre, 2011) and the auditory domain (Besle et al., 2011; Fujioka, Trainor, Large, & Ross, 2012; Henry & Obleser, 2012; Snyder & Large, 2005), and modulation of event-related potentials (ERPs) N1, N2, N2pc, P1, P300 and contingent negative variation (CNV) components (Correa, Lupiáñez, Madrid, & Tudela, 2006; Correa & Nobre, 2008; Griffin et al., 2002; Lange, 2010; Lange, Krämer, & Röder, 2006; Lange, Rösler, & Röder, 2003; Miniussi et al., 1999; Rolke, Festl, & Seibold, 2016; Sanders & Astheimer, 2008; Seibold, Fiedler, & Rolke, 2011; van Ede, de Lange, Jensen, & Maris, 2011). Interestingly, the pattern of the CNV observed in temporal orienting and timing tasks resembles the neural firing rates observed in motor and timing tasks in parietal (Janssen & Shadlen, 2005; Leon & Shadlen, 2003), motor (Renoult, Roux, & Riehle, 2006), premotor (Akkal, Escola, Bioulac, & Burbaud, 2004) and prefrontal regions (Niki & Watanabe, 1979), describing the overlapping of some of the anatomical areas involved in temporal orienting tasks additionally to the overlap with the networks involved in the spatial attention tasks mentioned above. Brain-imaging methods (positron emission tomography (PET) and functional magnetic-resonance imaging (fMRI)) have revealed that the left posterior parietal cortex along the intraparietal sulcus (IPS), the anterior inferior parietal lobule and the inferior premotor cortex form the neuroanatomical network implicated in the control of temporal attention (Cotti, Rohenkohl, Stokes, Nobre, & Coull, 2011; Coull et al., 2013; Coull & Nobre, 1998; Coull, Frith, Büchel, & Nobre, 2000; Davranche et al., 2011). Finally, it has been reported that temporal expectations regulate desynchronization of the alpha band activity regarding the anticipation of upcoming targets (Lima, Singer, & Neuenschwander, 2011; Rohenkohl & Nobre, 2011). The role of alpha band activity to anticipatory states in visual tasks has been previously described (Ergenoglu et al., 2004; Gould, Rushworth, & Nobre, 2011; Hanslmayr et al., 2007; Thut, Nietzel, Brandt, & Pascual-Leone, 2006; van Dijk, Schoffelen, Oostenveld, & Jensen, 2008), and the observed effects of temporal expectations on modulating alpha-band when anticipating a sensory stimulus, supports the importance of alpha-band oscillations may play in temporal expectations tasks (Busch & VanRullen, 2010; Lima et al., 2011; Mathewson et al., 2012; Praamstra et al., 2006; Rohenkohl & Nobre, 2011; van Ede et al., 2011).

Using the SSVEP as a tool to further understand the physiology behind temporal expectation will also extend our knowledge about how our brain deals with time to improve performance. In this thesis work, I implemented the SSVEP for the first time in a temporal attention study, manipulating time intervals to induce temporal expectations.

Space in attentional processing

The available literature, and particularly the significant amount of biological evidence, could reveal the direct relationship between numbers and automatic allocation of spatial attention. In that sense, important findings that reveal the cognitive interaction between observing numbers and the automatic shift of spatial attention have been reported. And the biological evidence to disentangle this relationship has provided some alternatives to better understand how numbers are represented in the brain, and why it might be that both processes, numbers and space, share overlapping anatomical networks. Nonetheless, there are remaining questions regarding the mental representation of numbers with respect to the specific conditions of the task: how this mental representation of numbers changes if the component conditions of the task are different, and what happens with the mental representation if the numbers used in the task are relevant for the task? In order to provide further evidence about numbers and spatial attention, to clarify some of these, and maybe address other open questions, in this thesis I will use for the first time the SSVEP technique to evaluate the role of numbers in the allocation of spatial attention under two different conditions: when numbers but not their magnitude is relevant for the task (**Chapter 4**) and when they are completely irrelevant for the task (**Chapter 5**). Therefore, in the following paragraphs I will provide a general background of spatial attention and mental representation of numbers and what has been reported in the literature regarding the automatic shift of spatial attention induced by numbers.

As described in the previous section, attention involves different mechanisms that support the selection and processing of particular stimuli coming from the surrounding context in order to improve performance. In this section I will describe how directing attention to a specific location in space –spatial attention– benefits the perception and processing of information according to the current goal. I will in particular focus on the mental representation of numbers, how they interact with the mental representation of space and how numbers have been related with the allocation of attention to a specific position in space. Thus, following this idea, I will start describing how allocating attention to a specific position in visual space determines the selection of what we perceive and how we perceive it. Part of the selection process and the benefits on processing selected information provided by spatial attention, seems to be related to the way how we deploy visual attention, particularly if we look for features such as color (Blaser, Sperling, & Lu, 1999), direction of motion (Pastukhov, Fischer, & Braun, 2009), shapes (Suzuki, 2003), and objects (Suzuki, 2001). Nonetheless, It has been reported that spatial attention improves texture segmentation at the selected location (e.g., Yeshurun, Montagna, & Carrasco, 2008), filtering and using relevant information from several stimuli (e.g., Guzman-Martinez, Grabowecky, Palafox, & Suzuki, 2012), spatial resolution and processing efficiency (e.g., Abrams, Barbot, & Carrasco, 2010; Castiello & Umiltà, 1992), and contrast sensitivity (Barbot, Landy, & Carrasco, 2011). This relation between space-based and object-based attention and how they interact has been proposed in different theories (See Bundesen, 1990; Compton & Logan, 1993; Logan, 1996 for details). **However, in this thesis I will describe spatial attention as one type of attentional processing.**

In general, allocation of spatial attention enhances the representation of information at the selected area while demoting the processing of irrelevant components. Although our ability to direct attention to that specific location in space seems to be a voluntary decision, this is not always the case: when an abrupt, unexpected change in the environment happens, directing our attention to it has been named stimulus-driven (exogenous or bottom-up) attention (Hickey, McDonald, & Theeuwes, 2006; Yantis & Hillstrom, 1994). And when we intentionally direct our attention to a selected stimulus related to the current task, it has been named voluntary (or endogenous or top-down) attention (Folk, Remington, & Johnston, 1992; Pestilli & Carrasco, 2005). This allocation of spatial attention occurs in a covert (without moving the eyes from an already selected point) or overt way (directing our gaze or head to the source of attention). Covert attention favors processing of selected information (e.g., improves searching; Carrasco & Yeshurun, 1998) at the attended location at the expense of the disregarded information at the unattended location.

These two types of spatial attention (i.e., endogenous and exogenous) are part of the covert attention system that facilitates the processing and selection of information. Endogenous covert attention can be transient when the conditions of the task require a fast voluntary allocation of the endogenous covert attention. Endogenous covert attention is a process that occurs voluntarily and lasts as long as needed to complete our task. Although covert endogenous attention can be sustained for several seconds, it is a slow process that takes between ~300-500 ms to be allocated to the selected location (Montagna, Pestilli, & Carrasco, 2009). On the contrary, exogenous covert attention is a faster process than endogenous covert attention, peaking around ~100-120 ms and decaying around ~250 ms (Nakayama & Mackeben, 1989; Remington, Johnston, & Yantis, 1992). The deployment of these two types of attention can be manipulated using spatial cues that could induce the observer to direct attention to a specific location in space before stimulus presentation. The use of cues for the study of spatial attention was first implemented by Posner (1980) in a seminal study where participants were requested to respond as fast and accurate as possible to the presentation of a peripheral target after the presentation of a central or peripheral cue. A brief peripheral presentation of a cue next to the possible target location induced an automatic exogenous allocation of attention while central cues pointed where to allocate attention voluntarily. And performance for both the endogenous and exogenous conditions was better for targets presented at the cued location (or valid trial) as compare when targets where displayed at the uncued location (or invalid trial; Posner, 1980b; Posner et al., 1980). Besides explicitly influence the allocation of spatial attention using cues (Posner,1980), allocation of spatial attention can also implicitly be influenced by following the specific attributes of the stimulus in time and space (Doherty et al., 2005).

According to this, only peripheral cues would induce an automatic shift of spatial attention while central cues could only induce voluntary allocation of spatial attention. However, it has been shown that for tasks where the spatial component is the most relevant the use of central cues with spatial features (e.g., gaze or arrows) can induce and automatic allocation of spatial attention even if the cue is irrelevant for the task (Friesen & Kingstone, 1998; Hietanen, Leppänen, Nummenmaa, & Astikainen, 2008; Hommel, Pratt, Colzato, & Godijn, 2015; Tipples, 2002). Interestingly, it has been reported that the use of numbers as central cues have an effect in allocation of spatial attention when presenting lateralized targets (Casarotti, Michielin, Zorzi, & Umiltà, 2007; Dodd, Van der Stigchel, Leghari, Fung, & Kingstone, 2008; Fischer et al., 2003; Schuller, Hoffmann, Goffaux, & Schiltz, 2015; van Galen & Reitsma, 2008). Additional supporting evidence for these results come from studies with patients with left hemispatial neglect who show bias in a number bisection tasks (Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; Zorzi, Priftis, & Umiltà, 2002). Allocation of spatial orienting when using numbers as a cue is influenced by the context and the particular parameters of the task (Galfano, Rusconi, & Umiltà, 2006; Ristic, Wright, & Kingstone, 2006).

Dehaene, Bossini & Giraux (1993) were the first to describe the mental representation of numbers as a mental number line (MNL) and the relation between numbers and the mental representation of space on what they termed the Spatial-Numerical Association of Response Codes (SNARC) effect. After their seminal study, the desire to understand the effect of numbers on spatial attention has steadily grown (see Bonato, Zorzi, & Umiltà, 2012 for a review). However, it was Fischer et al. (2003) who first described a direct relation between numbers and spatial attention, as proposed by MNL, and several follow-up studies have accepted the MNL to describe the SNARC effect (Chinello, de Hevia, Geraci, & Girelli, 2012; Göbel, Calabria, Farnè, & Rossetti, 2006; Hesse & Bremmer, 2017; Müller & Schwarz, 2007; Schwarz & Keus, 2004; Shaki, Fischer, & Göbel, 2012; Weis, Estner, van Leeuwen, & Lachmann, 2016; Zohar-shai et al., 2017; Zorzi, Priftis, & Umiltà, 2002). Nonetheless, it has been proposed that the SNARC effect and its relation with mental representation of space could also be explained by the stimulus response compatibility (SRC; Fitts & Seeger, 1953), the dual-route cognitive model (Gevers, Caessens, & Fias, 2005; Gevers, Ratinckx, De Baene, & Fias, 2006) or the polarity correspondence theory (PCT) of compatibility (Proctor & Cho, 2006).

The SRC view describes the SNARC effect as the result of the dimensional overlapping between stimulus and response options, which explains the effects on RTs and accuracy. In other words, responses improve if the stimulus and the response share common physical or conceptual features (e.g., stimulus and response button are on the same side) compared to when they don't (e.g., response button option is on the opposite side of the stimulus; Kornblum, Hasbroucq, & Osman, 1990). Thus the enhancement in behavior is not explicitly induced by the effect of numbers on allocating spatial attention with respect to the target. On the other hand, the dual-route cognitive model describes how two different cognitive routes (e.g., conditional and unconditional) of information processing automatically trigger the SNARC effect due to the association between number magnitude and response codes. The stimulus activates the appropriate response through the conditional route that relies on the instructions of the task, and is considered to be under voluntary control (e.g., congruent trials). The unconditional route automatically activates the spatial relation between stimuli and responses (e.g., incongruent trials). If both routes are activated in parallel and lead to a similar association between stimulus and response, task performance improves. On the contrary, if the routes do not converge, and different associations between stimuli and responses are elicited, then performance decreases. Finally, PCT describes the relative salience between each dimension (e.g., stimuli and response) over its perceptual or conceptual similarity. Thus, participants activate polarities ("+" or "-") of the different dimensions. If the assigned polarity to one dimension (e.g., stimuli) is the same as the one assigned to another dimension (e.g., response), then they are associated and therefore activated. In the case of a numerical representation, the "right" and "large" dimensions have polarity "+" and the "left" and "small" have polarity "-". Therefore, overlapping polarities between stimulus and response improves performance regardless of its spatial or perceptual representation. These approaches support the response target-stimulus related notion of the SNARC effect and, although all theories provide an explanation on how mental representation of space and mental representation of numbers interact, they do not provide a clear description about how numbers induce an automatic shift of spatial attention.

In spite of the aforementioned theories on how the mental representation of numbers (i.e., SNARC effect) interacts with spatial attention, and the behavioral studies that report the effects of numbers on inducing an automatic shift of spatial attention, there is no univocal physiological and/or neuroanatomical evidence supporting such direct interaction. On the contrary, the available information is very heterogeneous. Some ERPs studies described the SNARC as a process that arises during the selection of the response key, rather than during perceptual processing (Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; Gut, Szumska, Wasilewska, & Jaśkowski, 2012; Keus & Schwarz, 2005). An fMRI study reported no SNARC effect on the allocation of spatial attention (Goffaux, Martin, Dormal, Goebel, & Schiltz, 2012) and responses in the superior parietal cortex do not reveal a consistent relation between numerosity and the allocation of spatial attention responses (Harvey et al., 2013). Notwithstanding these findings, several studies have reported a neuroanatomical overlap between spatial and number processing. For example, it has been reported that the networks involved in number processing in the parietal lobe are also involved in spatial cognition (Chochon, Cohen, Moortele, Dehaene, & Inserm, 1999; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002), and the activation of occipital and intraparietal networks has been reported in tasks involving spatial and numerical processing (Hubbard, Piazza, Pinel, & Dehaene, 2005, 2009; Piazza, Mechelli, Butterworth, & Price, 2002; Pinel, Piazza, Le Bihan, & Dehaene, 2004). Results reported in studies on clinical populations support this overlap in the neuroanatomical networks involved in number processing and spatial attention (Arend, Ashkenazi, Yuen, Ofir, & Henik, 2017; Freund, 2001). Similarly, studies using ERP revealed the time course of spatial attention shifts induced by numerical cues (Ranzini, Dehaene, Piazza, & Hubbard, 2009).

Overall, the available literature provides an intriguing description of the mental representation of numbers, how our performance in a task that involves numbers (either if they are relevant or not) seems to be highly related to the way our brain represents numbers and space and how they interact. Also, there is a significant number of studies that describe how SSVEP provides a unique tool to measure fluctuations in spatial attention. Adding to the studies on spatial attention and mental representation of numbers (SNARC), I present in this thesis a new implementation of the SSVEP in parity and target detection tasks, both of which involve numbers, to provide physiological evidence about the role of numbers and spatial attention.

SSVEP in cognitive neuroscience

The electroencephalogram (EEG) is commonly used in cognitive electrophysiology, particularly for its high-temporal resolution, with SSVEP as one of the leading techniques. As SSVEP signal processing has been developing in the last decades, I will implement a novel approach for the data analysis of the SSVEP (Cohen & Gulbinaite, 2017). In the following paragraphs I will provide a general overview of SSVEP, and its implementation for studying visual attention, and describe the spatial filter implemented for the analyses reported in this thesis.

Recorded from the scalp, the evoked EEG potentials reflect changes in the brain’s electrical activity in response to sensory stimuli. Such potentials have become an important tool for studying the dynamic interaction between visual stimulation, the brain’s response to the latter, and how this brain activity describes human cognition (Handy, 2005; Luck & Kappenman, 2012). A specific type of evoked potential used in visual research is the SSVEP. It involves repeatedly flickering visual stimuli while measuring their EEG responses (like a strobe light, a.k.a. photic drive; Luck, 2005; Regan, 1989). The activity of large neural populations in the brain’s early visual processing areas will resonate at the same temporal frequency, and the recorded sinusoidal EEG response is called SSVEP (Regan, 1989). The SSVEP has been extensively used to study visual attention because the amplitude correlates with the amount of attention paid to the flickering stimulus (Andersen & Müller, 2010; Kashiwase, Matsumiya, Kuriki, & Shioiri, 2012; Kim, Grabowecky, Paller, Muthu, & Suzuki, 2007; Saupe, Schröger, Andersen, & Müller, 2009; Walter, Quigley, Andersen, & Müller, 2012). For example, if two panels are presented on a computer screen, one flickering at 15 Hz and another at 20 Hz, it is possible to determine to which panel one is attending by comparing the EEG responses at 15 Hz and 20 Hz. Moreover, in the study of cortical activation, when performing an attentional task with a flickering attended and/or unattended stimulus, it is possible to resolve these stimuli by recording SSVEP (Morgan, Hansen, & Hillyard, 1996): the attended stimulus has an increased SSVEP amplitude compared to the case when the stimulus is ignored (Müller et al., 1998). For example, Morgan et al. (1996) and Hillyard & Anllo-Vento (1998) presented to participants two squares that flickered at two different frequencies, at two different locations (left and right). When two streams of alphanumeric characters were superimposed on the flickering squares, the authors found that the SSVEP amplitude is affected by the degree of attention. The subject's task was to attend the stimulus at either the left or right stream of characters and covertly respond when they identified the target in the cued side of the screen. With these studies the authors demonstrated the attention-modulation effect on the SSVEP amplitude and it has been replicated in different studies across the field of visual attention (e.g., Garcia, Srinivasan, & Serences, 2013; Malinowski, Fuchs, & Müller, 2007; Müller, Malinowski, Gruber, & Hillyard, 2003; Müller, Bartelt, Donner, Villringer, & Brandt, 2003). This attention-modulation effect allows the extraction of a readily quantifiable signal in the frequency domain, from the EEG background activity, more rapidly than with other visual stimulation systems (e.g., transient Visual evoked potentials –VEPS; Regan, 1989).

In addition, to further elucidate the role of attentional processing in modulating SSVEP amplitude, the technique has been used to identify different functional subsystems that preferably respond to a specific stimulation frequency (Regan, 1989) and time-varying fluctuations in attention (Jamison, Roy, He, Engel, & He, 2015). Evidence for flickering sensitivity in the visual system has shown that an extensive range of frequencies can entrain visual responses (e.g., Herrmann, 2001 (1 - 100 Hz)). This facilitates the use of SSVEP as a frequency-tagging technique to isolate neural responses generated by different stimulus frequencies (e.g., Toffanin, de Jong, Johnson, & Martens, 2009).

Although changes in SSVEP amplitude are generally related to the effects of attention, Ding et al. (2006) suggested that attention modulation may depend on stimulation frequency as for frequencies in the lower alpha band (8 – 10 Hz) an increase in SSVEP amplitude can be found when the flickering frequency is peripheral to the attended target. This means that the effects of attention on the SSVEP may depend in part on the stimulus flicker frequency (Bridwell & Srinivasan, 2012; Srinivasan, Bibi, & Nunez, 2006). Subsequent studies have evaluated the effects of attention on SSVEP, using different flickering frequencies (Andersen & Müller, 2010; Andersen, Müller, & Hillyard, 2009; Chen, Seth, Gally, & Edelman, 2003; Gulbinaite, van Viegen, Wieling, Cohen, & VanRullen, 2017; Müller et al., 2006; Spaak, de Lange, & Jensen, 2014), providing further evidence for the specificity of the effects of attention modulation on SSVEP amplitude.

Finally, the SSVEP provides a high signal-to-noise ratio (SNR) measurement of brain activity and can be readily associated with specific stimuli, even if multiple stimuli are displayed at the same time (Norcia, Appelbaum, Ales, Cottereau, & Rossion, 2015).

SSVEP data analysis

The traditional approach to analyze SSVEP data is to compare results across electrodes and inspect their topographical distribution (Cohen, 2017). In spite of positive results by extracting and plotting the power spectra of single electrodes, some challenges to improve data analyses of the SSVEP have been reported. Cohen & Gulbinaite (2017) summarized them as: a) difficulty in the electrode selection across stimulation frequencies and individuals; b) small effects in the SSVEP SNR due to small stimuli and short presentation times; c) difficulties separating the SSVEP response from ongoing oscillations, particularly when the study aims to evaluate interference of the SSVEP with the ongoing neural oscillations; d) difficulties in the time series analysis of the time-course of the SSVEP due to the use of different band-filters; e) troubles separating different SSVEP frequencies when presented simultaneously; and f) the single trial analyses within subject cross-trial analyses. To resolve these challenges the authors presented the rhythmic entrainment source separation (RESS) technique (Cohen & Gulbinaite, 2017).

RESS is a method to analyze SSVEP responses maximizing the SNR of the narrow-band response in the frequency and time-frequency domain as compared with other methods (See Figure 1.1). More than being a new technique *per se,* RESS is a modification of different existing source separation techniques. The basic idea is to create linear spatial filters that are multiplied with the EEG electrode time series data to produce a single RESS component per frequency (this is a weighted combination of the electrodes). This is one of the advantages offered by the RESS filter: instead of analyzing data from a single electrode, the data of a weighted combination of all electrodes is contained in the RESS component (see Figure 1.2). The RESS method involves generalized eigendecomposition to construct an optimal spatial filter that maximizes the SSVEP effect. The eigenvector with the largest eigenvalue maximally differentiates two covariance matrices (a “signal-**S**” and a “reference-**R**” covariance matrix). Each eigenvector weighs the data from all the electrodes into a single component to maximize the power at the SSVEP frequency compared to neighboring non-stimulated frequencies. The obtained RESS component then can be analyzed in the time or in the frequency domain. Then the computation is $\mathbf{SW} = \mathbf{RW\Lambda}$, where $\mathbf{W}$ is the matrix of the eigenvectors and $\mathbf{\Lambda}$ is a diagonal matrix of eigenvalues. Importantly, the RESS components are not pairwise orthogonal because although $\mathbf{S}$ and $\mathbf{R}$ are symmetric matrices (which individually have orthogonal eigenvectors), the eigendecomposition is performed on $\mathbf{R}^{-1}\mathbf{S}$, which is not symmetric. The signal covariance matrix was obtained from the narrowband filtered data at each stimulus frequency and its second harmonics. The reference covariance matrix was obtained from data filtered at the closely spaced above and below nearest-neighbor frequencies. Constructing the reference matrix in this way provides an accurate SSVEP time course reconstruction. Similarly, because neural responses are topographically and anatomically different, compared to responses at the fundamental frequency, implementing RESS to separate SSVEP harmonics reduces possible confounding effects induced due to muscle artifacts, particularly at temporal and frontal electrodes.

Overall, as the SSVEP activity is spectrally and topographically stationary over time, the implementation of the RESS method is facilitated. Also, it is important to highlight that the temporal bandpass filtering of RESS, for SSVEP purposes, is more narrow compared to other spatial filters and the spatial filter in the RESS method is applied to broadband data (See Cohen & Gulbinaite, 2017, for details). The use of the RESS method in the SSVEP data analyses for all EEG studies presented in this thesis yielded high SNRs for all flicker frequencies, for both the fundamental and the second harmonic, even though the frequencies where displayed at the same time.

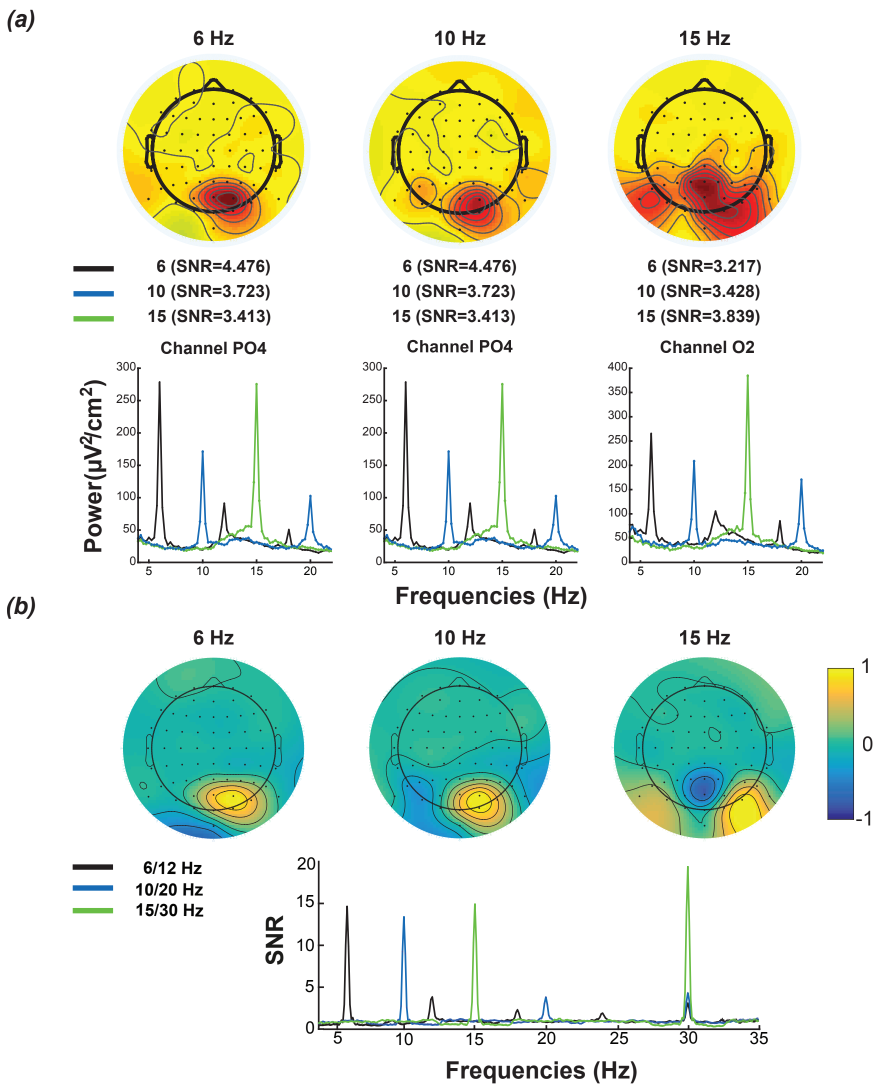


Figure 1.1. Comparison of the results obtained for one participant in the temporal attention task (Chapter 3) between the (a) best electrode and (b) RESS methods. The results obtained with the best electrode approach correspond to channels PO4, PO4 and O2 for the 6 HZ, 10 Hz, and 15 Hz flicker, respectively. Values on the *y* axis panel (a) correspond to the obtained power spectrum for the corresponding electrodes. The converted SNR values for each frequency and electrode are presented below the topographical map of the corresponding frequency. In panel (b) the values on the *y* axis correspond to power spectra converted to SNR units. The SNR obtained with the best electrode method (a) is smaller compared to that obtained with the RESS method (b). This difference between the two methods was also observed for the second harmonic for the three SSVEP frequencies. Similarly, the topographical maps show the difference in the EEG response obtained with the (a) best electrode approach and the (b) RESS method. Given the high SNRs obtained with the RESS method response at the second harmonics from the three flicker frequencies can be

observed. Although some responses can be observed for the second harmonic in panel (a), the SNR values were smaller (values not shown) than the SNR values obtained for the fundamental frequencies.

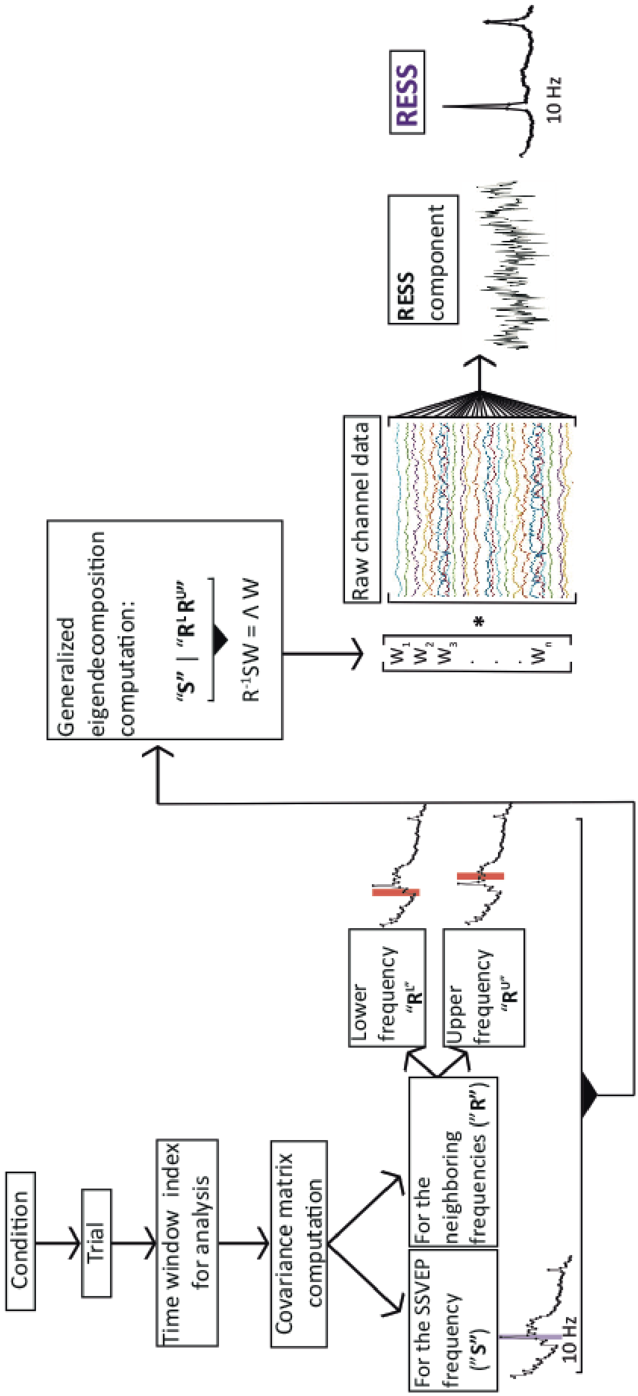

Condition
Trial
Time window index for analysis
Covariance matrix computation
For the SSVEP frequency ("S")
10 Hz
For the neighboring frequencies ("R")
Lower frequency "R^L"
Upper frequency "R^U"
Generalized eigendecomposition computation:
"S" | "R^L R^U"
R^-1SW = Λ W
W1 W2 W3 . . . Wn
*
Raw channel data
RESS component
RESS
10 Hz

Figure 1.2. Schematic representation of the step-by-step procedure in the Matlab code I implemented to perform the RESS method for the EEG SSVEP data analysis. For each condition, for the corresponding trial, first the time window index for analysis was selected. From the electrode data, the covariance matrices were computed for the SSVEP frequency ("S") and the closely spaced lower ("R^L") and upper ("R^U") neighboring frequencies. These covariance matrices are constructed from the narrowband band data at the SSVEP frequency (for this schema the 10 Hz is use as an example). The generalized eigendecomposition was performed to identify the eigenvectors (W) with the largest eigenvalues that separates the "S" covariance matrix (the SSVEP frequency) from the "R" covariance matrices (the neighboring frequencies R^L and R^U). Then, the eigenvectors with the largest values were used to multiply the raw data channel, that is, the eigenvectors were used as weights for combining all the electrodes, to obtain a single RESS component. After obtaining the corresponding RESS components, these were analyzed in the time and frequency domain as will be explained in the Methods section of each of the studies presented in this thesis.

AIM AND OUTLINE OF THIS THESIS

To understand how our brain processes and selects information to produce a proper response is one of the goals of cognitive neuroscience. To this end, several techniques for studying cognitive processes such as attentional processing and temporal predictability have been suggested among which we note behavioral testing and noninvasive electrophysiological recording. Because cognitive processing can change rapidly (within a fraction of a second), electroencephalography (EEG) with a temporal resolution in the order of milliseconds is a widely used brain-imaging tool for studying human cognition, among which the steady-state visual evoked potential (SSVEP) is a common technique. In this thesis, results are reported that were obtained with SSVEP during a temporal and spatial attention task while simultaneously recoding EEG.

The overarching aim of my PhD research is to use the SSVEP technique in a novel setting to better understand the psychophysiological processes behind temporal expectations and spatial attentional processing. Number stimuli were overlaid with targets flickering at different frequencies and used to shed light on the relation between endogenous brain oscillations and attentional processing. Increasing our understanding of the cognitive and biological aspects of cognition, in healthy as well as in clinical populations, is expected to extend our knowledge about the processes behind them and to lead to applications from which clinical populations could benefit.

In **chapter 2** I review a communication alternative that relies on attentional processing and that can be used for both healthy and physically impaired people with intact attention, a brain-computer interface (BCI) in the context of natural language processing, and different techniques to improve the BCI system, including the ones based on SSVEP.

In **chapter 3** describes a novel implementation of SSVEP in a temporal attention task. Here I provide evidence for using SSVEP to better understand the role of temporal expectations in response times and in perception, and in this way extend our current knowledge on how time influences performance.

Chapter 4 describes another novel implementation of SSVEP, this time to better understand the interaction between mental representations of numbers and space, specifically to provide physiological evidence for the hypothesis that numbers induce an automatic allocation of spatial attention. The hypothesis is tested in a parity judgment task.

Chapter 5 reports on the behavioral and physiological results of a target detection task where numbers were irrelevant to the task. The main outcome of chapters 4 and 5 is that, when numbers are part of the task, although their magnitude is not, they have an effect on spatial attention in a parity judgment task, while this was not the case for tasks where numbers were completely irrelevant to the task as in the target detection task.

Finally, in **chapter 6**, I summarize and discuss the main findings of the studies reported in this thesis, indicate the implications for our current knowledge about temporal attention and the interaction between spatial attention and numbers, and list a number of recommendations for future studies.

Chapter 2

Language Model Applications to Spelling with Brain-Computer Interface: Review

Abstract

Within the Ambient Assisted Living (AAL) community, Brain-Computer Interfaces (BCIs) have raised great hopes as they provide alternative communication means for persons with disabilities bypassing the need for speech and other motor activities. Although significant advancements have been realized in the last decade, applications of language models (*e.g.*, word prediction, completion) have only recently started to appear in BCI systems. The main goal of this article is to review the language model applications that supplement non-invasive BCI-based communication systems by discussing their potential and limitations, and to discern future trends. First, a brief overview of the most prominent BCI spelling systems is given, followed by an in-depth discussion of the language models applied to them. These language models are classified according to their functionality in the context of BCI-based spelling: the static/dynamic nature of the user interface, the use of error correction and predictive spelling, and the potential to improve their classification performance by using language models. To conclude, the review offers an overview of the advantages and challenges when implementing language models in BCI-based communication systems when implemented in conjunction with other AAL technologies.

Keywords: Ambient Assisted Living; Brain-Computer Interfaces; spelling systems; electroencephalography; communication systems; language models

Based on: *Mora-Cortes, A., Manyakov, N., Chumerin, N., & Van Hulle, M (2014). Language Model Applications to Spelling with Brain-Computer Interface. Sensors, 14(4). https://doi.org/10.3390/s140405967*

INTRODUCTION

A Brain Computer Interface (BCI) enables a user to communicate with the external world by directly translating his/her brain activity into (computer) commands without relying on the brain's normal output pathways. Due to this, BCIs have raised great hopes in providing alternative communication means for persons suffering from motor disabilities such as amyotrophic lateral sclerosis (ALS), spinal cord injuries or brain paralysis (Allison & Pineda, 2003; Wolpaw et al., 2000; Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002), and other users targeted by the Ambient Assisted Living (AAL) community (Hintermüller, Guger, & Edlinger, 2011), provided their sensory and cognitive functions are still intact (Birbaumer & Cohen, 2007). Since one of AAL's aims is to improve the quality of life of elderly persons with disabilities, BCI systems have become an opportunity to achieve this via different AAL implementations of BCI systems (Hintermüller et al., 2011; Navarro et al., 2011; Ortner, Guger, Prueckl, Grünbacher, & Edlinger, 2010; Serbedzija, 2010). A BCI system in general (see Figure 2.1) normally comprises the following components: (i) a device that records the brain activity which is either invasive (*e.g.*, electrocorticography) or non-invasive (*e.g.*, electroencephalogram-EEG); (ii) a *preprocessor* that reduces noise and artifacts, prepares the signals for further processing and extracts the relevant information from the recordings; (iii) a *decoder* that classifies the extracted relevant information into a control signal for (iv) an *external device* that could be any type BCI-compatible application (*e.g.*, a robotic actuator, a prosthesis, a computer screen *etc.*), and that provides feedback to the user. This *external device* could also be used for evoking brain activity, thus serving as a *stimulation unit* (see Section 2 for examples). The feedback to the user is an important aspect of the BCI system as it provides the former with information about mistakes (by the decoder or the user) and in this way motivates the user to better modulate his/her brain activity and to increase attention and engagement in the task, thus adhering to a so-called *neurofeedback* principle. As a result, the BCI can be regarded as a control system with active feedback (closed-loop system).

The first BCI was presented in the pioneering work of Vidal (1973), where the basic requirements of a man-machine communication tool and the concepts, feasibility, possibilities and even its limitations were already introduced. Since then BCI applications have ramified into different areas such as clinical/translational research (from basic research to clinical BCI implementations; Mak & Wolpaw, 2009), entertainment (Chumerin et al., 2013), ambient assisted living (Navarro et al., 2011), and emerging applications such as bionic assistive devices (Kapeller et al., 2013), and the detection of covert behavior, among others (see Brunner, Bianchi, Guger, Cincotti, & Schalk, 2011 for a review).

Since invasive BCI requires surgery and faces not only ethical but also technical challenges, it has rarely been performed on humans (Collinger et al., 2013). It therefore comes as no surprise that the non-invasive alternative became widely adopted in human BCI-based communication research. Among all noninvasive BCIs, the EEG-based ones are favored above other non-invasive ones such as functional magnetic resonance imaging (fMRI; Weiskopf et al., 2004), magnetoencephalography (MEG; Graimann, Allison, & Pfurtscheller, 2010) and functional near infrared spectroscopy (fNIRS; Coyle, Ward, & Markham, 2007; Khorshidtalab & Slami, 2011). The advantages of EEG led to a rapid increase in the number of BCI research groups all over the world (Wolpaw, 2007) as reflected by the share in the number of publications in the field in the last decade (Fazel-Rezai et al., 2012; Konrad & Shanks, 2010), and have spurred the interest in developing feasible and practical BCI systems, as covered in several review papers (Becedas, 2012; Cecotti, 2010; Fazel-Rezai et al., 2012; Pasqualotto, Federici, & Belardinelli, 2012; Rak, Kołodziej, & Majkowski, 2012), and some of which have been implemented within AAL applications as control environment (Navarro et al., 2011) and social interaction (Hintermüller et al., 2011). More specific reviews focus on communication issues (Brunner et al., 2011; Cecotti, 2010, 2011; Mak et al., 2011; van Gerven et al., 2009), signals related issues such as their processing (Bashashati, Fatourechi, Ward, & Birch, 2007; Krusienski et al., 2011; Nicolas-Alonso & Gomez-Gil, 2012), feature extraction (Khorshidtalab & Salami, 2011; Lotte, Congedo, Lécuyer, Lamarche, & Arnaldi, 2007), brain potentials (Vialatte, Maurice, Dauwels, & Cichocki, 2010), neuroimaging-based BCI (Min, Marzelli, & Yoo, 2010), handling artifacts (Bashashati et al., 2007) and decoding methods for BCI systems (Tonet et al., 2008; Ying, Sherry, & Hui, 2011). Nonetheless, to the best of the authors' knowledge, there is no comprehensive review of the applications of language models in BCI systems despite of the increasing research interest in this direction (for more detalied reviews of BCI systems see Allison, Wolpaw, & Wolpaw, 2007; Nicolas-Alonso & Gomez-Gil, 2012; Rak et al., 2012; Wolpaw et al., 2000).

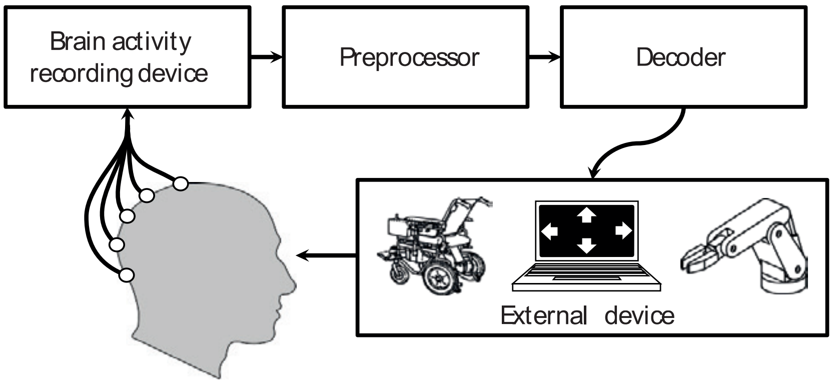


Figure 2.1. Brain-Computer Interface scheme.

The aim of this article is to review the available literature that combines language models with BCI systems for communication applications. Since research in this direction has been performed only for EEG-based BCI, we also limit ourselves to this case. Nevertheless, all language modelling strategies discussed below could in principle also be used in other BCI types, including different AAL applications (*e.g.*, controlling environment). The focus of this paper is on BCI spellers (which are systems allowing users to type individual characters, words or even sentences by decoding their brain activity) combined with applications such as word prediction, completion, error correction, and so on, which may increase the communication speed without increasing the user's cognitive load. These new approaches offer a significant advantage over other augmentative and alternative communication (AAC) devices, which at least require some degree of motor activity (Felton et al., 2007; Sellers, Vaughan, & Wolpaw, 2010).

PARADIGMS FOR BCI COMMUNICATION SYSTEMS

One of the main applications for BCI is spelling. These spelling systems are mainly based on one of three BCI paradigms, exploiting different types of brain responses: *event-related potentials* (ERP), *steady state evoked potential* (SSVEP) or *frequency visual evoked potential* (f-VEP) and *motor imagery* (MI).

ERP-Based BCI

The most known representative of this group is the so-called P300-speller. The idea behind it derives from the observation that a stereotypical component of brain potential is evoked in response to an infrequent stimulus attended by the user, while it is absent for a frequent but non-attended stimulus. The main difference in responses is seen in a positive deflection around 300 ms following onset of the stimulus, the so called P300 component, which is primary generated above the parietal and central cortices (Farwell & Donchin, 1988). This phenomenon is present for visual (Allison & Pineda, 2003), auditory (Höhne, Schreuder, Blankertz, & Tangermann, 2011) or tactile stimulations (Brouwer & van Erp, 2010; Chatterjee, Aggarwal, Ramos, Acharya, & Thakor, 2007), which led to different BCI interaction modes. A first speller of this type was a visual one, proposed in (Farwell & Donchin, 1988). In such visual P300-spellers a 6 × 6 matrix with characters is displayed with rows and columns intensified in random order (see Figure 2.2) with about 5–6 intensifications per second (Farwell & Donchin, 1988; Speier, Arnold, Lu, Taira, & Pouratian, 2012). The user attends to one of the symbols he/she wishes to communicate. The intensification of the row/column that contains the desired character evokes an enhanced P300 component (Farwell & Donchin, 1988). The trained (in advance) classifier detects the row-column combination for which the P300 response is present and selects the character accordingly. The recorded signal is a superposition of the activity related to the stimulus and all other ongoing brain activity together with noise, which makes single-trial ERP detection very difficult. In order to more robustly detect ERPs, recordings over several row/column intensification rounds need to be averaged. By averaging the activity that is time locked to a known event (*e.g.*, the onset of the attended stimulus) is extracted as an ERP, whereas the activity that is not related to the stimulus onset is expected to be averaged out. The speed with which characters can be typed therefore heavily depends on the number of rounds needed to extract the P300 component accurately. Although such BCIs are mainly regarded as P300-based, other components of evoked potentials also play important role in decoding (Treder & Blankertz, 2010).

BCIs based on *rapid serial visual presentation* (RSVP; Acqualagna & Blankertz, 2013; Acqualagna, Treder, Schreuder, & Blankertz, 2010; Cecotti et al., 2011; Chennu, Alsufyani, Filetti, Owen, & Bowman, 2013) could also be categorized as ERP-based BCI. RSVP-based BCI uses visual stimuli presented with a rate of about 10 stimuli per second (Acqualagna et al., 2010; Cecotti et al., 2011; Chennu et al., 2013), among which user attends to the only stimulus he/she wish to communicate. Stimuli are rapidly displayed in a one-by-one basis in the same predefined position known to the user in order to avoid necessity for their search and eye movements, as they could produce artifacts in the EEG recordings. The user has to attend the desired stimulus and mentally count the number of times it is presented. The decoding procedure is similar to the P300-based case.

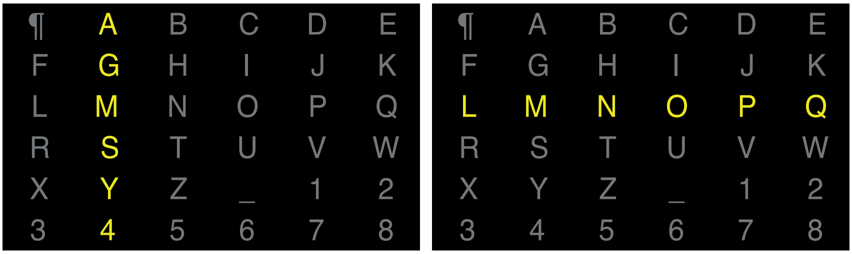


Figure 2.2. Example of typing matrix in P300-speller. Rows and columns are intensified in random order. The intensification of the second column (Left panel) and the third row (Right panel) are shown. One round consists of the intensification of each one of the six columns and six rows.

BCI based on *motion-onset* (Guo, Hong, Gao, & Gao, 2008; Hong, Guo, Liu, Gao, & Gao, 2009; Jin, Allison, Wang, & Neuper, 2012; Schaeff, Treder, Venthur, & Blankertz, 2012) and *transient visual evoked potentials* (t-VEP) BCI (Liu, Goldberg, Gao, & Hong, 2010) also fall in this BCI category and utilize quite similar processing and decoding techniques. Motion-onset VEP is evoked by the presentation of motion stimuli (Heinrich, 2007), and its main components have been described as P100, N200 and P200 (Kuba, Kubová, Kremláček, & Langrová, 2007). The t-VEPs are the responses recorded from the visual cortex after a visual stimulus has been displayed(Regan, 1989) and the amplitude of the visual response increases every time the target is closer to the subject's central visual field (Wang, Wang, Gao, & Hong, 2006).

Much research has been directed towards achieving a higher detection accuracy of brain evoked responses to target stimuli for an equal or lower number of intensification rounds. This research was primary performed in the *preprocessing component* (see Figure 2.2), searching for a better spatial and frequency filtering or a better feature selection and construction methods (Chumerin, Manyakov, Combaz, Suykens, Yazicioglu, et al., 2009; Chumerin, Manyakov, Combaz, Suykens, & Van Hulle, 2009; Rivet, Souloumiac, Attina, & Gibert, 2009; Zhang et al., 2013), on the *classifier component* (Manyakov, Chumerin, Combaz, & Van Hulle, 2011), and in the design of the *external-stimulation device*, *e.g.*, by adapting the inter-stimulus interval (Farwell & Donchin, 1988), the size of the matrix (Allison & Pineda, 2003) and the intensification protocol (Aricò et al., 2011; Fazel-rezai & Abhari, 2009; Guan, Thulasidas, & Wu, 2004; Townsend et al., 2010).

ERP-based BCIs are also known by the fact, that those systems do not necessary depend on the gaze direction, *i.e.*, they could rely on covert attention instead (Acqualagna & Blankertz, 2013; Aricò et al., 2011; Höhne et al., 2011).

BCIs based on Frequency and Code Modulation of VEP

The *steady-state visual evoked potential* (SSVEP) or *frequency visual evoked potential* (f-VEP; Bin, Gao, Wang, Hong, & Gao, 2009), recorded above the occipital cortex, is the response to a periodic presentation of a visual stimulus (*i.e.*, a flickering stimulus). When the stimulus is flickering at a sufficiently high rate (starting from 6 Hz), the individual evoked responses to each stimulus flash will overlap, leading to a steady-state signal resonating at the stimulus flicker rate and its integer multipliers (harmonics; Luck, 2005). With such a paradigm it is possible to detect whether a subject is looking at a stimulus flickering at frequency f, by verifying the saliency of the frequency f and possibly also its harmonics, $2f, 3f, \ldots$ in the spectrum of the recorded EEG signal. Similarly, one can detect which stimulus, out of several of them (each one flickering at a different frequency), is gazed at by the subject, by checking the corresponding frequencies and their harmonics. Linking each flickering stimulus to a particular command, a multi-command frequency-coded SSVEP-based BCI can be implemented. For example, one can construct a speller by dividing the screen into quadrants, flickering at different frequencies, which contain different subsets of characters (Figure 2.3). The user gazes at the quadrant that contains the desired character (Segers et al., 2011), allowing the selection of any character (here out of 64) by performing consecutive quadrant selections (three for Figure 2.3).

Since in the spectral domain the EEG amplitude decreases as the frequency increases, the higher stimulus frequencies and harmonics become less prominent. Furthermore, the SSVEP is embedded in other ongoing brain activity and (recording) noise (Segers et al., 2011). Thus, when considering a recording interval that is too small to reliably extract the frequency components, erroneous detections are quite likely to occur. To overcome this problem, averaging over several recording intervals (Manyakov, Chumerin, Combaz, Robben, & Van Hulle, 2010), or recording over longer time intervals (Wang et al., 2006) are often used together with a spatial filtering strategy (Friman et al., 2007; Garcia-Molina & Zhu, 2011; Volosyak, 2011) to increase the signal-to-noise ratio (SNR).

An efficient SSVEP-based BCI speller should be able to reliably detect several frequencies, which makes the detection issue even more complex, calling for efficient signal processing and decoding algorithms. This has primary led to modifications in the preprocessing and classifier components of Figure 2.1.

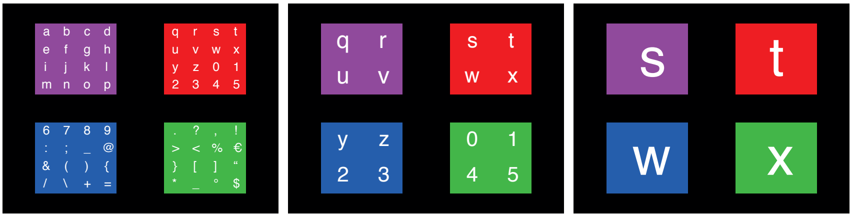


Figure 2.3. Three consecutive stages to select symbol “w” in a SSVEP speller.

An additional limitation arises from the stimulation side: only stimulation frequencies within a particular frequency range evoke a reasonable SSVEP response (Jia, Gao, Hong, & Gao, 2011); the harmonics of some stimulation frequencies could interfere with one another, leading to a deterioration of the decoding performance (Volosyak, Cecotti, & Gräser, 2009), even more so when the stimulation frequencies depends on the refresh rate of the screen (Volosyak, Cecotti, & Gräser, 2009) (in the case of stimulation on a computer screen). This encouraged the search for alternative stimulation methods in computer screen based SSVEP BCIs (Wang, Wang, & Jung, 2010) or other encoding methods (Jia et al., 2011; Manyakov et al., 2013; Manyakov, Chumerin, & Van Hulle, 2012), thus, modifying the stimulation (external) device block in Figure 2.1.

Another VEP-based technique adopted by BCIs is called *code modulated VEP* (c-VEP) originally proposed by Sutter (1984) and further developed by others (Bin et al., 2011, 2009; Spüler, Rosenstiel, & Bogdan, 2012a). Following c-VEP approach to induce most distinguishable visual responses to different target stimuli, the intensity of the stimuli is modulated by a special pseudorandom binary sequence, so-called m-sequence, which is designed to be nearly orthogonal with respect to its shifted versions. This m-sequence and its (circularly) shifted versions are then used to modulate visual stimulation to induce discernible brain responses. The processing of the c-VEP responses involves averaging across several epochs, where each epoch corresponds to one full presentation of the m-sequence during stimulation. The decoding step usually relies on simple template matching technique: the preprocessed (filtered and averaged) c-VEP response is matched against several pre-computed templates, corresponding to the target stimuli, and the winner is selected as the best matching one.

Some other classification methods (*e.g.*, one class SVM, canonical correlation analysis) have been proposed (Spüler et al., 2012a) to improve the performance of c-VEP BCIs.

More detailed descriptions of c-VEP techniques as well as RSVP, motion-onset, and t-VEP techniques can be found in (Acqualagna et al., 2010; Bin et al., 2009; Guo et al., 2008; Liu et al., 2010; Spüler, Rosenstiel, & Bogdan, 2012b).

MI-Based BCI

A *motor imagery* (MI) BCI is based on changes in neural populations in the motor cortex when performing an actual or imagined limb movement. These changes are hypothesized to be due to decrease (event-related desynchronization, ERD) or an increase (event-related synchronization, ERS) in the synchrony of the underlying neuronal populations (Pfurtscheller, 1977, 1992). In spectra of EEG, recorded above motor cortex contralaterally to moved (or imagined to be moved) body part (*e.g.*, left arm), this (imaginary) movement produces a decrease in power (ERD) in the mu (8–13 Hz) and beta (13–26 Hz) band in comparison to the absence of such movement or its imagination (Pfurtscheller & Lopes da Silva, 1999). As such, by determining changes in spectral amplitudes in the corresponding frequency bands or, equivalently, in the variance of the EEG signal filtered in the same band one can determine the subject's intentions (Pfurtscheller & Neuper, 2001). In addition to ERD/ERS, the readiness potential (Bereitschaftpotential) has also been used for the decoding of motor imagery (Blankertz, Dornhege, Krauledat, Müller, & Curio, 2007; Pineda, Allison, & Vankov, 2000).

By involving two or more different limbs, for example, the right and left hands, and relying on the fact that different parts of the motor cortex are responsible for different limbs (*i.e.*, they are spatially distributed), one can build a BCI system. In order to enhance the detectability of the MI, different fixed- (McFarland, McCane, David, & Wolpaw, 1997), data-driven (Ang, Chin, Zhang, & Guan, 2008; Higashi & Tanaka, 2013; Ramoser, Müller-Gerking, & Pfurtscheller, 2000), multi-class (Yi et al., 2013) spatial filtering approaches have been proposed, as well as different classifiers (Dornhege, Krauledat, Müller, & Blankertz, 2007), thus mainly modifying the *Preprocessor* and *Decoder* blocks of Figure 2.1. A detailed review of spatial filtering and classification techniques for MI-based BCIs can be found in (Li, Xu, Zhang, Guo, & Yao, 2013; Yu, Chum, & Sim, 2014).

Several MI-based spelling devices have been proposed. For example, D'Albis et al. (2012) used a typing interface consisting of 26 characters of the English alphabet and a "space" (thus, 27 symbols in total) equally divided into three groups (see Figure 2.7b). The user selects one of those three groups or the "undo" command by imagining the movement of the corresponding body part(s) (in their case the right hand, left hand, both hands or both feet). By selecting one of these groups, the nine characters are divided into three new groups of three characters. And so on. Thus, typing one character takes three consecutive selections, similar to the SSVEP speller described above in Section *BCIs based on Frequency and Code Modulation of VEP*.

Another MI-based BCI-speller is the so-called Hex-o-Spell (Blankertz et al., 2006), with which 30 different characters can be typed by imagining one of two movements (right hand and foot; see Figure 2.4). The characters are shown in six adjacent hexagons distributed around a circle. Each hexagon contains five characters and a "go back" command. For the selection of the hexagons, there is an arrow in the center of the circle. Right hand movement imagination controls the rotation of the arrow clockwise. The imagination of the foot movement extends the arrow until it reaches one of the hexagons after which it is selected. After this, the characters in all hexagons, except for the selected one disappear, while the remaining characters and the "go back" command are mapped into six hexagons around the circle, *i.e.,* the same layout as in the beginning. Using the same arrow-based strategy, the user selects the desired character or decides to go back to the previous level of the interface to correct a mistake.

LANGUAGE MODEL IN BCI SPELLERS

As discussed before, the conventional approach to improve the communication speed and accuracy of a BCI speller is to search for new and better signal processing and classification algorithms, or to change the stimulation mode or stimulation parameters, thus, modifying the blocks in Figure 2.1. Albeit successful to some extent, BCI spellers still cannot compete with their assistive technology counterparts. This prompts for alternative solutions beyond the ones covered by traditional BCI research. One such solution was indicated by Donchin and coworkers (Donchin, Spencer, & Wijesinghe, 2000): "*It is well known that there are substantial sequential dependencies in English. It is our intent to incorporate information about the sequential structure of the language in the next phase of the development of the BCI. Similarly, it is possible to incorporate spelling correction software so that spelling mistakes can be managed even as increases in the operational speed may be associated with increased number of errors*." While this was proposed already in 2000 and seemed quite promising, until recently there were no attempts to adopt language model strategies. In the following subsections, we describe recent developments and implementation of language models for BCI spellers.

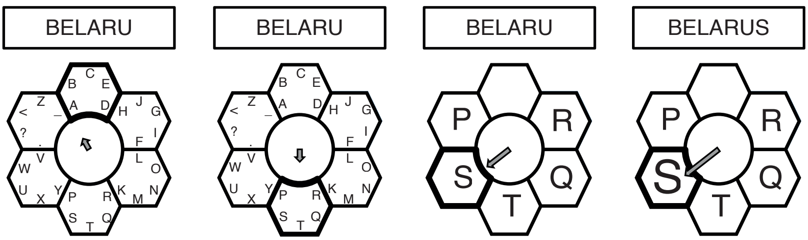


Figure 2.4. Two different types of imaginary movements allow the user to control the rotation and extension of the gray arrow in the Hex-o-Spell interface. In this example the last letter in the word "BELARUS" is selected. Adapted from (Blankertz et al., 2006).

Language-Driven Design of Static User Interfaces

As a basic implementation of language models in BCI spellers, one can mention the way characters are arranged in the spelling interface. The characters' layout could rely on the initial probability of occurrence of a character in a particular language or on the aim to minimize typing mistakes with respect to some dictionary. Such a layout is fixed and does not change during typing (whence "static"). The corresponding interfaces are dependent on the BCI paradigm adopted.

An example that accounts for the relative frequency of character occurrence in a language, consider the interface of the Bremen SSVEP-based BCI-speller (Volosyak, Cecotti, Valbuena, & Gräser, 2009). It has in the middle of the screen a virtual keyboard with 32 symbols (see Figure 2.5) surrounded by five boxes flickering at different frequencies. These boxes correspond to commands for navigating the cursor (indicated by red colour) "left", "right", "up", "down", and for selecting the intended character. The application starts with a cursor in the central position corresponding to the most frequent character in English ("E", in Figure 2.5). By gazing at the command boxes, the user can navigate the cursor to the desired letter and confirm his/her choice with the "select" command. The further the character is located from the center, the more command selections (cursor movements) are required. Letters with the higher frequency of occurrence are positioned closer to the center while the less frequent ones are further away.

Moreover, attentional switches are also taken into account. For example, two commands (left-left) are required to reach the letter "A" and the same amount of commands (left-up) to reach the letter "M". But in the latter case the user has to redirect his/her gaze from the command box "left" into command box "up", while in the former case such a redirection of the gaze is not required, which is more easy for the user. Considering this, the more frequent letter "A" (8.167% according to Beker & Piper, 1982) is positioned in a more easily reachable position than the less frequent letter "M" (2.406% according to Beker & Piper, 1982). By accounting for the initial letter probability in a language the user can more easily and much faster select the intended characters with this interface, which in turn results in a higher throughput of the system.

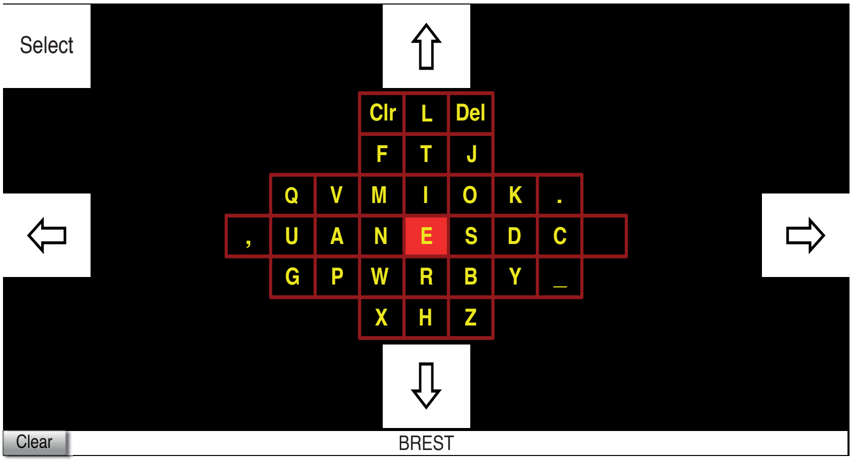
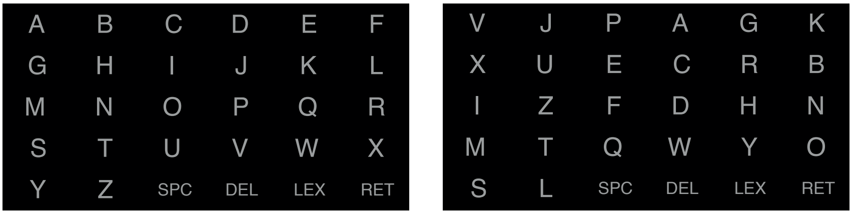


Figure 2.5. Layout of the Bremen SSVEP-based BCI-speller. Adapted from (Volosyak, Cecotti, Valbuena, et al., 2009)

Another way to place characters in static interface, but this time for a P300 row-column speller, was proposed in (Ahi, Kambara, & Koike, 2011). The authors tried to modify the spelling matrix by taking into account the notion that the majority of errors in a row-column paradigm occur either by wrongly selecting a row or a column (Manyakov et al., 2011). The idea was to displace as much as possible letters which are different in similar words proved by a dictionary attached to the speller. For example, the words HINT and HUNT are similar, since they differ only in the second letter. While using the conventional interface of Figure 2.6a, one can see that letters “I” and “U” are in the same column. In the modified interface of Figure 2.6b neither the row, nor the column for the letters “I” and “U” coincide. In this way, with a conventional interface, while typing the word HINT and making mistakes in the second letter, one could end up in the wrong word HUNT, even when the column is identified correctly (but not the row), but in the case of the modified interface, a row or column misclassification during the selection of the second letter in the word HINT will not lead to a conventional English word. This could be an indication that a decoding mistake was made, which could be rectified, *e.g.*, by using the algorithm described in Section *Spelling Error Correction.*

Dynamic Adaptation of User Interface

The user interfaces discussed in Section *Language-Driven Design of Static User Interfaces* are static ones, *i.e.*, they do not change during the spelling process. However, it is known that the probability of a letter in a word depends on the previously typed ones. For example, if one has already typed ENGL, it is not likely to have X as the next letter, while it is quite probable to have I as the next letter (for example, the word ENGLISH). Thus, the probability of each letter in a language is not fixed *a priori*, but varies during spelling. This idea was employed in the group of methods described below, all of which perform dynamic adaptations of the user interface, depending on the already (partially) spelled text.

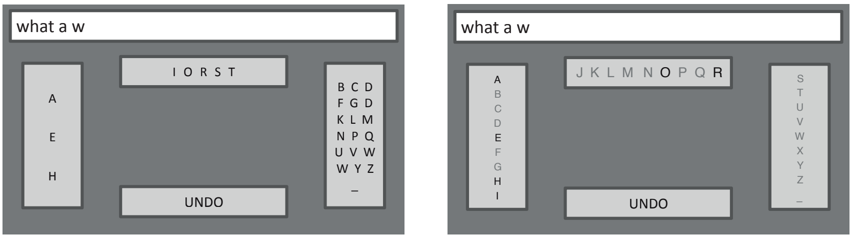


(a) (b)

Figure 2.6. Conventional (**a**) and modified (**b**) P300-speller interfaces used in the study of Ahi and colleagues . Adapted from (Ahi, Kambara & Koike, 2011).

In addition to their standard interface (see Section *MI-Based BCI* for a description), D’Albis et al. (2012) also foresaw dynamic modifications by incorporating a language model for taking into account the changing probability of the next letter l_n in the currently typed word, based on the already typed characters of the same word $l_1, \ldots, l_{n-1}$ (prefixes) and the two typed preceding words w_1 and w_2. These modifications are based on an algorithm that extracts from the corpus (*corpus* is a large set of texts used for linguistic analysis), attached to the speller, all possible distinct triples of words, where the first two words are w_1 and w_2, and the first $n-1$ letters in the third word are $l_1, \ldots, l_{n-1}$. When estimating the probability of having the next letter l_n, the number of selected triples goes to the denominator while the numerator is equal to the number of triples, among the selected ones, where additionally the n-th letter in the third word is l_n. As an example, let us assume one wants to type the phrase "what a wonderful day", and the two first words "WHAT" (w_1) and "A" (w_2) were already typed. In the third word, the first letter "W" (l_1) was also typed, and the user intends to type the second letter (l_2) (see Figure 2.7). The algorithm scans the corpus in order to find all triples following "WHAT A W…" (where the dots represent any further characters within the third word, starting with the letter "W") and estimates the number N of such triples. Among the found ones, the algorithm also estimates the number of those that take the form of "WHAT A WA…" (for l_2 = "A"), "WHAT A WB…" (for l_2 = "B"), and so on. By dividing these numbers by N, the algorithm generates an estimate of the probability for any letter l_2 to be the next one. All letters with nonzero probability were enabled in the interface (see D'Albis et al., 2012 for further explanation). In the example in Figure 2.7, after typing "WHAT A W" the algorithm detected a nonzero probability only for the letters "A", "E", "H", "I", "O", "R" (ranked by their estimated probabilities), which are considered as the only likely choices for the next character.

The dynamic interface (Figure 2.7a) then rearranges the candidate characters in descending probability (where the first three most probable letters are grouped together, and so on) in order to minimize the number of subsequent group expansions. The static interface (see Figure 2.7b) does not change the character layout, but instead disables the ones with zero estimated probability. This interface could be regarded as more comfortable for the subject, since it does not require attentional shifts. Both interfaces enable the user to pick the next letter "O" just by two selections (instead of three in the normal mode), thus making spelling faster.



(a) *(b)*

Figure 2.7. Dynamic (**a**) and static (**b**) interfaces for a system, that considers previously typed text "what a w" for spelling the next letter. Adapted from Blakertz et al. (2006).

Another strategy that accounts for the previously spelled characters in BCI speller can be based on the Dasher interface (Ward, Blackwell, & MacKay, 2000), which originally employed 2D control. When the pointer (black arrow) is at the centre of the screen (indicated by the crosshair), nothing is happening. As soon as the user moves the pointer to the right, the letters on the right hand side of the screen start to zoom in (see Figure 2.8, showing consecutive screenshots while typing the string "Hello"). The vertical position of the pointer controls the direction in which zooming is performed and the pointer's horizontal position controls the speed of zooming. If one moves the pointer back to the centre of the screen, the spelling process pauses, when moving the pointer to the left side of the screen mistakes can be corrected by moving back in the already typed sequence.

The Dasher interface shows symbols that are more probable in the current context by enlarging the square region around them. In the initial stage, the probabilities (size of the squares) of each symbol are taken from the frequencies of each symbol in an adjusted corpus. This makes the Dasher interface different from the one from (D'Albis et al., 2012), since it additionally incorporates the strategy discussed in Section *Language-Driven Design of Static User Interfaces.* Probabilities of consecutive symbols are estimated with the use of an *n*-gram (*n-gram* is an adjacent sequence of *n* item from a whole sequence.) language model on character's basis; by assessing from the attached corpus and based on previously typed text the probabilities $c_1c_2...c_{n-1}c$, where c is the next symbol to be typed, and c_i are the previously typed symbols. An additional difference with the approach from D'Albis et al. (2012) is also the fact that all symbols (not only letters) are considered, *i.e.*, "space", punctuations and other symbols are assumed to be c_i's. In this way, the sequence $c_1c_2...c_{n-1}c$ could also have symbols not only from the word currently being typed (as in D'Albis et al., 2012), but also from the ones that are part of the preceding word(s), and spaces and other punctuation symbols between those words.

The idea of using a Dasher interface in a BCI-speller was first mentioned by Wills and MacKay in 2006, but no real BCI application was presented in the paper. Nevertheless, in their paper they acknowledged a potential problem with the inferior 2D control in BCIs, and discussed ways to perform 1D control instead. They suggested either using a special mapping of 1D input into 2D, as required in Dasher, or to fix the zooming speed and allow for only vertical control with the BCI interface. With the latter strategy, one can divide the Dasher interface into several vertically distributed zone-stimuli (as for the case of SSVEP or P300 BCI), and when one of those zones is selected, the pointer will move into the corresponding region for zooming (Wills & MacKay, 2006). In real on-line typing, Dasher was evaluated when using motor imagery BCI and the 1D to 2D mapping strategy (Felton et al., 2007), and when using SSVEP-based BCI (with constant horizontal speed) constructed around only one flickering stimulus for vertical control, where gazing at the stimulus is associated with moving upwards, while no gazing leads to moving downwards (Angel, Bojorges-Valdez, & Yanez-Suarez, 2011).

The approaches mentioned so far in this subsection are based on a probability assessment of the next symbol by aggregating statistics from the attached corpus. As an alternative approach (Mathis & Spohr, 2007), one can try to exclude any statistical information and construct in advance a *trie* (*trie*, derived from re*trie*val, is an ordered tree data structure used mainly for managing strings in memory) lexicon structure from the corpus. Mathis and Spohr (2007), using all words from the corpus, constructed the trie, where starting from the root node (associated with an empty string) and by moving down to descendant nodes and further on, one can "read" all words from this corpus. When constructed in this way, a trie is another representation of all words from a corpus. When used in a BCI-speller, when the user is typing, any entered string is monitored and associated with the corresponding node in the trie. If the current node has only a single edge exiting from it, the corresponding next character (associated with this edge) is incrementally added to the already typed text. Thus, such a strategy allows adding a uniquely determined next character, speeding up the text spelling process. For example, if one wants to type the word UNIQUE, after spelling UNIQ the next letter "U" will be added automatically, since it is the only possible continuation of the previously typed sequence in English. Mathis and Spohr in (2007) used this strategy in a simulated P300 speller and found that, on average, every eighth character was added automatically, allowing to speed up the typing process, while retaining a very low rate (0.84%) of wrong word completions.

Figure 2.8. Five successive stages when entering "Hello" with the Dasher interface.

Minimization of Command Selections by Using T9-Like Interface

T9, which stands for Text on 9 keys (Dunlop & Crossan, 2000), is a language interface developed by Tegic Communications ("Nuance Communications") for text entering on mobile phones. This system was designed to enable typing of more than 30 different characters with only numerical keys on a mobile phone's keypad. Each key corresponds to several characters. For example, if one wants to type HOME then, with the T9 interface, where key "4" corresponds to "G", "H", "I", key "6" to "M", "N", "O" and key "3" to "D", "E", "F", he/she needs to select keys 4663. After this, T9 looks through an attached dictionary in order to find all words corresponding to this sequence of key presses, and ranks them by their frequency of use. For example, 4663 corresponds to HOME, GOOD, GONE… The most frequent words are presented to user for selection (the exact number of those words depends on interface). The T9 system modifies the word frequencies depending on the user, by increasing word frequencies according to the history of typing, and also allows for typing new words that are subsequently added to the dictionary. Thus, the T9 interface minimizes the number of keystrokes, which is a big advantage for BCI-spellers with limited number of commands to select from (*i.e.*, stimuli). While the system initially was called T9, it actually uses 12 keys: keys 2–9 for letters, other keys for punctuation, space and other characters.

Höhne and co-workers (2011) used the T9 system for an auditory ERP-based speller, where a 3 × 3 spelling matrix was encoded by three levels of sound pitches (high, medium and low) for the rows and three directions of sound (left, middle and right) for the columns. They changed the original T9 interface in order to use only nine keys instead of 12. In spelling mode, keys 2–9 were connected to letters, as in an ordinary T9, but key 1 was for switching the interface to a mode in which keys 4–8 encode five most frequent words suggested by T9, and keys 1–3 and 9 correspond to punctuation, backspace, delete and exit, respectively.

A similar system was also implemented in the visual P300 Chinese speller (Jin et al., 2010). In this system, each symbol can be spelled with five strokes used for writing any Chinese symbol. After typing the intended sequence of strokes, the seven most frequent Chinese words were presented to the user for selection.

Predictive Spelling Module in BCI Spellers

This approach is based on the psycholinguistic cohort model proposed in (Marslen-Wilson, 1987). The model states that when a person hears or reads a segment (consisting of several consecutive letters) of a word, all words from his/her lexicon starting from this segment are "activated" in his/her brain. The more letters are added to the segment, the fewer words remain "activated". Thus, by adding more and more letters to the segment, the "activation" is narrowing down to only one word, *i.e.*, the one that coincides with the word being read or heard.

Such a psycholinguistic model could be used for a spelling interface when the interface is connected to some dictionary or corpus (*i.e.*, the user's lexicon is replaced by words from this dictionary or corpus). When the user has typed the first letters of the intended word, all words from the attached dictionary that share the same first letters are "activated", and the most frequent words among them are presented to a target list from which the user can select. The user then can either further type the intended word letter-by-letter with the BCI speller, or select the intended word as soon it appears in the list. In this way, one expects the user to be able to spell faster, since not always the whole word needs to be typed character-by-character.

Depending on the interface, the word suggestion list could be presented either on separate layout, than the one for character-by-character spelling (Akram, Metwally, Han, Jeon, & Kim, 2013; Volosyak, Moor, & Gräser, 2011), which requires an additional BCI command to switch between those two layouts, or it could be incorporated into the ordinary layout, thus not requiring any additional switches, which saves time (Kaufmann, Völker, Gunesch, & Kübler, 2012; Ryan et al., 2011).

Similar to other alternative and augmentative communication (AAC) devices (Koester & Levine, 1994; Venkatagiri, 1994), a BCI predictive spelling may increase the user's cognitive workload (Akram et al., 2013; Ryan et al., 2011). This was observed in P300 spellers, where a list of suggested words was displayed, but they were not used directly as a stimuli for selection, but the words were labeled by numbers 1–7, and the subject had to type the corresponding number in order to select one of those words (see Figure 2.9a; Akram et al., 2013). By modifying the interface, so that words from the list are integrated directly into interface, thus they are used as the stimuli, the above mentioned problem could be alleviated (see Figure 2.9b; Kaufmann et al., 2011).

When word suggestions are shown to the user, they are visualized by presenting only a few of the most likely ones based on the system's lexicon. Those frequencies could initially be equal for all words in the lexicon and change according to the typed text (Volosyak, Moor, & Gräser, 2011; Ryan et al., 2011), or they could be different and depend on word frequency, derived from the corpus used for compiling the lexicon (Kaufmann et al., 2011). Moreover, the word frequencies could be estimated for each word separately (Kaufmann et al., 2011), *i.e.*, not taking into account the context, or by also accounting for one or more preceding words (D'Albis et al., 2012), *i.e.*, an *n*-gram model on words basis.

Spelling Error Correction

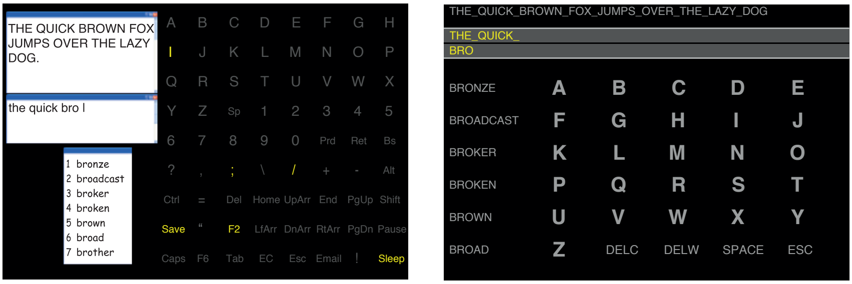
While typing with a BCI, it could happen that the interface misclassifies and consequently mistypes the symbol intended by the user. As a result, for an ordinary BCI speller, one needs to foresee a "backspace" command for correction, or to use some brain potential connected to the subject's realization of an error (Error-related Potential) followed by some smart algorithm for correcting the mistyped character (Combaz et al., 2012). As yet another alternative, one might not perform any correction, but continue to type while relying on an incorporated language model that performs the correction automatically at a later stage.

The latter was explored in Ahi, Kambara & Koike (2011) for the P300 speller thereby assuming that for each spelled word the start and end points are determined correctly (*i.e.*, number of letters in typed word is correct). While typing each letter, BCI speller estimates probabilities of each letter to be intended by subject according to classifier outcomes, and rank them in descendent order according to these probabilities. When a whole word is spelled, a search through the attached dictionary is performed, and for each candidate word the sum of the above mentioned ranks of each letter in this word is computed. The word with the smallest sum of ranks is then selected as the mostly likely intended ("corrected") word.

Other systems also allow for a correction of misspelled words to some extent. The word prediction module described in Ryan et al. (2010), which was discussed in the previous section, is based on the word prediction software WordQ2 (Nantais, Shein, & Johansson, 2001), developed by Quillsoft Ltd. ("GoQ Software"). This software allows, for example, for the wrongly typed word "PLOS" (while the user intended to type "PLEASE") to be included as the word "PLEASE" in the list of suggestions, hence, enabling the user to correct errors when using predictive spelling module technology (Ryan et al., 2010).

Incorporation of Character Prediction Statistic into Classifier

It could also be possible to fuse the classifier with some natural language model. For example, assume one has typed the segment "WH" (the beginning of the word "WHAT") and the next letter detected by the classifier is "T". In this case it is not wise to present such a letter to the user since English does not have any word starting with "WHT". Since it is clearly a mistake, it is better to use knowledge of what is possible and what not in a given language directly at the level of the classifier.



(a) *(b)*

Figure 2.9. Two different layouts designed for predictive spelling. (**a**) The predicted words are displayed on the left side of the screen over an "extra" window in the interface, thus requiring keeping them in the user's memory, which could increase the cognitive workload. Adapted from Ryan et al. (2010). (**b**) The solution proposed to alleviate the cognitive workload by integrating the suggested words into the interface as selectable stimuli. Adapted from Kaufmann et al. (2012).

One can use an *n*-gram characters model for assessing, using the attached corpus, the probability of each possible character typed by taking into account the previously typed segment of length *n*−1 characters. Considering the previous example with "WH" and an 3-gram model, the system scans the corpus and counts all occurrences of "WHA", "WHB", "WHC", … , "WHZ", "WH ", "WH.", … After that, the probability of having as the next letter an "A" is estimated as the number of occurrences of "WHA" compared to the sum of all mentioned triples starting with "WH". Such probabilities could be incorporated into the classifier by using, for example, a Bayesian interference strategy (Kindermans, Verschore, Verstraeten, & Schrauwen, 2012; Orhan et al., 2011; Samizo, Yoshikawa, & Furuhashi, 2012; Speier et al., 2012), thus for "correcting" the classifier output.

ASSESSMENT OF BCI SPELLERS BASED ON LANGUAGE MODELS

When assessing the benefits of incorporating additional technology into a BCI system, such as the ones based on language models, it is important to use some measure for characterizing the performance gain. A traditional measure such as typing accuracy is not adequate, as it does not provide any information about the spelling speed, which is an important usability characteristic. The *information transfer rate* (ITR), proposed in Wolpaw et al. (2002), takes into account the accuracy, the number of possible selectable commands the interface supports, and the time required for communicating one command (one interface selection). But the ITR leads to ambiguities for some speller interfaces, such as for the one proposed in (McFarland et al., 2000; shown in Figure 2.5). In such an interface, the number of possible commands could be either five (since five SSVEP stimuli are used for letter selection by moving the cursor left, right, up and down and for validating the selection) or 32 (if each character is considered to be selectable; Cecotti, Volosyak, & Gräser, 2009). Moreover, if one types text with a

BCI, it is sometimes required to use "backspace" for correction. While using additional commands, as "backspace", is seen as undesirable, the correct selection of the "backspace" command will increase the ITR of the assessed system, as pointed out in Dal Seno, Matteucci, & Mainardi (2010). In addition, if one wants to compare character-by-character typing with a word completion strategy, a new problem arises. In character-by-character typing four selections corresponds to maximally a four-letter word (if no mistakes occur), but the same four selections in a word completion strategy could result, for example, in a ten-letter word when, after spelling the first three letters, on a character-by-character basis, the fourth selection was used for choosing a ten-letter word from the list of suggestions. The ITR will treat the two cases in the same way, while it is clear that the latter one is much more beneficial. As a remedy, one could use the time spent on spelling some text (D'Albis et al., 2012).However, in general, in different studies the spelled texts are usually different, and therefore we cannot use this time-based measure to compare different BCI-spellers.

Ryan and colleagues proposed (2010) to use the *output character per minute* (OCM) measure, which is estimated by taking the ratio of the total number of characters in the final text to the total time spent on spelling this text. They showed that while the standard ITR indicates a decrease from 19.39 ± 5.37 bit/min to 17.71 ± 5.38 bit/min by switching from character-by-character to predictive spelling, the OCM measure is more appropriate and characterizes the benefit obtained by incorporating a language model by an increase from 3.71 ± 0.75 character/min for character-by-character mode to 3.76 ± 0.75 character/min for predictive spelling.

Another strategy to overcome the limitation of the standard ITR measure in the case of text spelling was proposed by Kaufmann and colleagues (2012). Instead of estimating the ITR in terms of selections per minute, they suggested to estimate the true bit rate in terms of the communicated characters per time unit. They showed that in their experiments the standard ITR was only slightly better for predictive spelling (15.7 ± 5.7 bit/min) compared to character-by-character spelling (15.1 ± 5.6 bit/min), while the true ITR better characterized the benefits of the language model by producing 20.6 ± 5.3 bit/min for predictive spelling and 12.0 ± 2.7 bit/min character-by-character spelling.

So far there is no consensus what measure to use. Different studies exploit different techniques for performance assessment. In Table 2.1 we list the performance data of the reviewed studies, where the results with and without natural language models are indicated. Since the performance of a BCI-speller depends on several components (*e.g.*, classifier, preprocessing and so on, see Section PARADIGMS FOR BCI COMMUNICATION SYSTEMS), we wanted to show only the effect of the language model while the other system components (like classifier, signal processing,…) remain the same.

Discussion

As is seen from Table 2.1, incorporating language models into BCI-spellers provides benefits in performance. In this way, language models could be seen as another way to improve the performance, in addition to a better classifier, more advanced signal processing, and so on. While the latter conventional methods are intended to change one of the blocks in Figure 2.1, the incorporation of a language model could be seen, in the majority of cases (for Sections *Dynamic Adaptation of User Interface – Incorporation of Character Prediction Statistic into Classifier*), as an additional block in the scheme, which could also influence the classification step, its outcome, or the interface (display layout) itself.

Studies done so far with language models in BCI spellers only had a small amount of words/characters typed (less than 60 characters). Therefore, it is difficult to draw any solid and unbiased conclusions about the benefits of language models during a prolonged use of the system. However, one could expect that in this case the user could become more familiarized with the interface and its abilities and caveats.

Moreover, some interfaces (Akram et al., 2013; Ryan et al., 2010) allow for the inclusion of the user's most frequent words and phrases, collected when using the BCI system, which could also speed up typing, especially in a word completion mode. On the other hand, with some of the language model implementations, as in Ryan et al. (2010), which were reported to increase the mental workload, the performance could even decrease after prolonged use. All these points indicate the necessity to perform longitudinal studies to properly evaluate the benefits of such implementations.

Even to date the potential benefits (if any) of some language models are not yet fully investigated. For example, the Dasher interface (see Section *Dynamic Adaptation of User Interface*) is merely presented as a proof of concept for BCI. Whether it is beneficial or not still remains an open question. Additionally, some evaluations and comparisons were only done with simulated BCI spellers (Blankertz et al., 2006; Mathis et al., 2007) or with off-line data (Speier et al., 2012; Orhan et al., 2011). All this still calls for on-line assessments of the proposed methodologies.

While the primary goal of BCI is to help patients suffering from locked-in syndrome, severe speech or motor disabilities, all studies with language models done so far only considered healthy subjects. It could very well be that some of the suggested methodologies, such as word completion, which require an increased cognitive load (Ryan et al., 2014), are in fact infeasible for certain patient groups.

Another challenge is the design of an appropriate interface, tailored to the user. This could even start with the selection of the corpora so that the interface is better tuned to the user's language or his/her language capabilities. Human-machine interaction studies in this direction are needed. It would also be beneficial to have interfaces that work without requiring the user to switch between different interface layouts as, for example, in Volosyak et al. (2011).

Such modifications could result in faster typing, since no commands for switching between interfaces are required. From the reviewed publications it is already seen that, for example, the list of word suggestions (during predictive spelling), integrated directly into interface, can reduce the mental workload (Kaufmann et al., 2012). All these could inspire the design and implementation of an interface that complies to with the main goals of AAL: to render the resulting system easily usable by the targeted user and not to increase its mental effort.

Most of the publications to language models in BCI spellers explore mainly only one of the language models presented in Section *Language Model in BCI Spellers*, while it is desirable to use several of them simultaneously to boost the performance. For example, a classifier for typing consecutive letters that takes into account letter probabilities depending on previously typed text (Section *Incorporation of Character Prediction Statistic into Classifier),* could be easily connected to predictive word spelling (Section *Predictive Spelling Module in BCI Spellers*). The same principle of implementing several applications, according to the particular needs of AAL users, can be followed when integrating BCI spellers in AAL applications (*e.g.*, in areas of safety, social environment, housework).

While the previous remarks are somewhat general, each method has its limitations and possible directions for improvement. For example, in Volosyak et al. (2011) the word prediction model was supported by a dictionary containing the 49,142 most common words in English. This dictionary consisted of (mainly) the singular form of those words, whereas the user sometimes wanted to type words in plural. Since the word completion strategy used in this study had each word completed by adding a space after it, many users preferred the character-by-character spelling mode over the word completion one, since the latter required frequent corrections, by using the "backspace" command, and a retyping to obtain the plural form.

As another example, we mention the word correction strategy proposed in Ahi, Kambara & Koike (2011) which can work under the following conditions: (a) the spelling system must exactly know where the intended word starts and ends (thus, a misspelled word-separating symbol could be considered as a part of the intended word); (b) the words can only contain letters (no digits and/or other characters); and (c) words not from the system dictionary are not supposed to be spelled. If at least one of these conditions is violated, then the described word correction strategy will be useless and will lead to a wrong textual output. Hence, further research is needed to overcome these limitations.

The potential benefits of BCI have been exploited in different BCI systems (Bin, Gao & Wang, 2009) including AAL applications. Particularly, BCI-spellers are in a position to improve the quality of life of people with particular communication needs (Navarro et al., 2011) as is the case in the AAL community. Additionally, the various implementations of language models (*e.g.*, completion, design of appropriate interfaces, avoid the switching between interfaces layouts, predictive characters selection) on BCI-spelling systems, as described in this review, could offer new ways to interact with assistive living, communication and control systems. Such implementations could support an active social environment in the context of rehabilitation (Hintermüller et al., 2011), and AAL applications such as control environment and context awareness (Ortner et al., 2010).

Table 2.1. Difference in performance of spelling interfaces with and without natural language models. The third column refers to the sections where they are discussed.

Study	BCI Paradigm	Section Describing Model	Number of Subjects	Amount of Words/Characters Typed	Performance without Natural Language Model	Performance with Natural Language Model
Kaufmann *et al.* 2012	ERP-based	Predictive Spelling Module in BCI Spellers	19	9 words / 45 characters	15.1 ± 5.6 bit/min (ITR) 12.0 ± 2.7 bit/min (true ITR)	15.7 ± 5.7 bit/min (ITR) 20.6 ± 5.3 bit//min(true ITR)
Ryan *et al.* 2010	ERP-based	Predictive Spelling Module in BCI Spellers	24	Sentence with 58 characters	19.39 ± 5.37 bit/min (ITR) 3.71 ± 0.75 char/min (OCM)	17.71 ± 5.38 bit/min (ITR) 3.76 ± 0.75 char/min (OCM)
Volosyak *et al.* 2011	SSVEP	Predictive Spelling Module in BCI Spellers	7	Three phrases with in total 34 characters	29.98 ± 5.79 bit/min (true ITR)	32.71 ± 9.18 bit//min (true ITR)
Ahi *et al.* 2011	ERP-based	Spelling Error Correction	14	10 words with 4 characters each	For 2 trials: 8.48 bit/min (ITR)	For 2 trials: 35.24 bit/min (ITR)
Ahi *et al.* 2011	ERP-based	Spelling Error Correction + Language-Driven Design of Static User Interfaces	14	10 words with 4 characters each	For 2 trials: 8.48 bit/min (ITR)	For 2 trials: 55.32 bit/min (ITR)
Speier *et al.* 2012	ERP-based	Incorporation of Character Prediction Statistic into Classifier	6	9 words with 5 letters each	22.07 ± 8.48 bit/min (ITR)	33.15 ± 12.37 bit/min (ITR)
D'Albis *et al.* 2012	MI	Dynamic Adaptation of User Interface	3	Phrase with 20 characters	12:56 min (spelling time)	10:38 min (spelling time)
D'Albis *et al.* 2012	MI	Predictive Spelling Module in BCI Spellers	3	Phrase with 20 characters	12:56 min (spelling time)	6:27 min (spelling time)
D'Albis *et al.* 2012	MI	Dynamic Adaptation of User Interface + Predictive Spelling Module in BCI Spellers	3	Phrase with 20 characters	12:56 min (spelling time)	6:09 min (spelling time)
Akram *et al.* 2013	ERP-based	Predictive Spelling Module in BCI Spellers	4	10 words	2.9 min (word spelling average time)	1.66 min (word spelling average time)

CONCLUSION

In this study we reviewed several approaches to boost the performance of existing BCI spellers by using language models. We categorized them based on the language model used and the way it is integrated. Different methods for assessing and comparing the performance of BCI spellers were discussed and adaptations to better account for the integrated language models suggested. We conclude that as a result of application of these language models, a significant improvement in spelling performance can be achieved, and new avenues of BCI integration in the AAL community charted such as social and environment control and rehabilitation.

ACKNOWLEDGEMENTS

A.M.C. is supported by the Administrative Department of Science, Technology and Innovation, Colciencias call 529/2011 (Colombia); N.V.M. is supported by the Flemish Regional Ministry of Education (Belgium) (GOA 10/019); N.C. is supported by the Flemish Agency for Innovation by Science and Technology (TETRA project Spellbinder); M.M.V.H. is supported by research grants received from the program Financing program (PFV/10/008) and the CREA Financing program (CREA/07/027) of the KU Leuven, the Belgian Fund for Scientific Research—Flanders (G088314N, G0A0914N), the Interuniversity Attraction Poles Programme—Belgian Science Policy (IUAP P7/11), the Flemish Regional Ministry of Education (Belgium) (GOA 10/019), the Flemish Agency for Innovation by Science and Technology (TETRA project Spellbinder), and by the SWIFT prize of the King Baudouin Foundation of Belgium.

AUTHOR CONTRIBUTIONS

A.M.C. performed the literature search and wrote the initial version of the manuscript. N.V.M. also contributed to the literature search and the structure of the paper, proposed the classification of the discussed models and reworked the manuscript. N.C. also reworked the manuscript and adapted the figures from the literature. M.M.V.H. contributed to the contents and structure of the paper.

DECLARATION OF INTEREST STATEMENT

The authors declare no conflicts of interests in any of the studies reported within this review.

Chapter 3

Evaluating the feasibility of the steady-state visual evoked potential (SSVEP) to study temporal attention

"Organisms are basically rhythmical and possess their own temporal structures which are manifested psychologically in a series of tunable perceptual rhythms"
(Mari Riess Jones, 1976)

Based on: *Mora-Cortes A, Richard Ridderinkhof K, Cohen MX. Evaluating the feasibility of the steady-state visual evoked potential (SSVEP) to study temporal attention. Psychophysiology. 2018;55: e13029. https://doi.org/10.1111/psyp.13029*

ABSTRACT

Improvements in perceptual performance can be obtained when events in the environment are temporally predictable—and temporal predictability improves attention and sensory processing. The amplitude of the steady-state visual evoked potential (SSVEP) has been shown to correlate with attention paid to a flickering stimulus even if the flickering stimulus is irrelevant for the task. However, to our knowledge, the validity of the SSVEP to study temporal attention has not been established. Therefore, we designed an SSVEP temporal attention task to evaluate whether the SSVEP and its temporal dynamics can be used to study temporal attention. We used a forced choice perceptual detection task while presenting task-irrelevant visual flicker at alpha (10 Hz) and two surrounding frequencies (6 or 15 Hz). Temporal predictability was manipulated by having the inter-stimulus intervals (ISI) be constant or variable. Behavioral results replicated previous studies confirming the benefits of temporal expectations on performance for trials with constant ISI. EEG analyses revealed robust SSVEP amplitudes for all flicker frequencies, although a main effect of temporal expectations on SSVEP amplitude was not significant. Additional analyses revealed temporal predictability-related modulations of SSVEP amplitude at 10 Hz and its second harmonic (20 Hz). The effect of temporal predictability was also observed for the 6 Hz flicker, but not for 15 Hz for any ISI condition. These results provide some evidence for the feasibility of the SSVEP technique to study temporal attention for stimuli with flicker frequencies around the alpha band.

Keywords: Attention, EEG, methods, SSVEP

INTRODUCTION

Time is crucial for brain and cognitive function. Our ability to perceive and interpret the world is largely determined by our ability to predict, perceive, and attend to changes over time. The ability to allocate our brain resources to perceive and attend to the predicted onset of a particular event while ignoring nonrelevant stimuli has been named temporal attention (Babiloni et al., 2004). Temporal attention can be maximized when events in the environment are temporally predictable (Coull & Nobre, 1998; Miniussi, Wilding, Coull, & Nobre, 1999; Rohenkohl, Coull, & Nobre, 2011).

Temporal expectancies have been extensively studied in the laboratory using an adaptation of Posner's spatial orienting task (Posner, 1980; Posner et al., 1980). The manipulation of cue timing can induce temporal expectations and participants are able to use such cues to predict the time-onset of the upcoming stimulus. Temporal expectations induced by the cue can be generated by using predictive (Davranche et al., 2011), instructive (Coull & Nobre, 1998) or rhythmic stimulation (Rohenkohl et al., 2011; Rohenkohl & Nobre, 2011). Also, manipulating hazard rates (Vangkilde et al., 2013) or the regularity or inter-stimulus interval between presentations (Jepma et al., 2012) could generate temporal expectations.

Temporal expectations have been shown to improve attention and sensory processing across different domains (Woodrow, 1914). For example, in a predictive visual temporal attention task using different time intervals for central cues that would predict next target presentation, Miniussi et al. (1999) reported that participants showed faster reaction times for trials predicted by shorter time cues (e.g., 600 ms) as compared with longer time cues (e.g., 1400 ms) or trials where the target was unpredictable (e.g., cue for 600 ms and target presented at 1400 ms). Similarly, Doherty et al. (2005) studied the effects of spatial and temporal expectations on visual attention processing. By using rhythmic cues, the authors manipulated expectations regarding location and/or time of target appearance after being briefly occluded by a barrier presented in the screen. The authors reported faster reaction times for all the expectation conditions (e.g., spatial, temporal or combined spatial and temporal expectation) as compared with conditions that lacked such expectations.

This general phenomenon of improved performance has been replicated several other times showing the effects on perceptual sensitivity (*d'*) during a rapid-serial-visual-presentation task (Correa et al., 2005), on reaction times when using symbolic (Griffin et al., 2001) or rhythmic cues (Doherty et al., 2005; Mathewson et al., 2012; Mathewson, Fabiani, Gratton, Beck, & Lleras, 2010), or the enhancement of temporal expectations when combined with spatial attention-orienting tasks (Doherty et al., 2005; Rohenkohl, Gould, Pessoa, & Nobre, 2014). Regarding the neurophysiology of temporal attention, several studies have described the left inferior parietal cortex (Coull & Nobre, 1998), intraparietal sulcus (Davranche et al., 2011), premotor and supplementary motor areas and a network of bilateral frontoparietal areas (Coull et al., 2000; Coull & Nobre, 2008) as key neuroanatomical regions responsible for temporal expectations. Modulatory effects of temporal expectancies on the event-related potentials N1, N2, N2pc, and P300 (Griffin, Miniussi, & Nobre, 2002; Miniussi et al., 1999; Rolke, Festl, & Seibold, 2016; Seibold, Fiedler, & Rolke, 2011; Seibold & Rolke, 2014; see Correa, Lupiáñez, Madrid, & Tudela, 2006 for details), and event-related synchronization/desynchronization of the ongoing EEG (Babiloni et al., 2004; Rohenkohl & Nobre, 2011) components have previously been described in several electrophysiological studies.

Although these approaches have helped to better understand the neural correlates of temporal attention and its role on perceptual processing, an alternative technique, the steady state visual evoked potential (SSVEP), has, to our knowledge, never been used to study temporal attention. The SSVEP is a rhythmic neural response that tracks a flickering sensory stimulus (a.k.a. photic drive; Luck, 2005; Regan, 1989) and can be induced with a flickering stimulation in the range from 1 to 100 Hz (Herrmann, 2001).

The SSVEP is a robust method to study visual perception (Ales, Farzin, Rossion, & Norcia, 2012), spatial (Müller & Hillyard, 2000) and selective attention (Hillyard et al., 1997; Silberstein et al., 1990), cognitive fatigue (Mun, Park, Park, & Whang, 2012), and working memory (Gulbinaite, Johnson, de Jong, Morey, & van Rijn, 2014). Similarly, the attentional effects on SSVEP have also been evaluated in performance for brain-computer interfaces (Mora-Cortes, Manyakov, Chumerin, & Van Hulle, 2014) and evaluated in clinical studies in patients with schizophrenia (Silberstein et al., 2000).

The SSVEP has been extensively used to study visual attention because the amplitude of the SSVEP correlates with attention to each flickering stimulus (Andersen & Müller, 2010; Ding, Sperling, & Srinivasan, 2006; Kashiwase, Matsumiya, Kuriki, & Shioiri, 2012; Kim, Grabowecky, Paller, Muthu, & Suzuki, 2007; Morgan, Hansen, & Hillyard, 1996; Müller, Teder-Sälejärvi, & Hillyard, 1998; Saupe, Schröger, Andersen, & Müller, 2009; Senkowski, Saint-Amour, Gruber, & Foxe, 2008; Vialatte, Maurice, Dauwels, & Cichocki, 2010; Walter, Quigley, Andersen, & Müller, 2012). Additionally, the SSVEP provides a high signal-to-noise ratio (SNR) measurement of brain activity and can be readily associated with specific stimuli, even if multiple stimuli are displayed at the same time (Norcia et al., 2015). And SSVEPs can be used to study time-varying fluctuations in attention (Jamison et al., 2015; Keil & Heim, 2009; Talsma, Doty, Strowd, & Woldorff, 2006; Wieser & Keil, 2011).

Although changes in SSVEP amplitude are generally related to attention, there is some evidence that this effect may depend on the stimulation frequency (Bridwell & Srinivasan, 2012; Ding et al., 2006; Srinivasan et al., 2006). In other words, the effects of attention on the SSVEP may depend in part on the stimulus flicker frequency, even if the flickering stimulus is irrelevant for the task. Furthermore, the alpha band (~10 Hz) has been described to be part of the substrate of temporal attention (Busch & VanRullen, 2010; Mathewson et al., 2012; Rohenkohl & Nobre, 2011) and ongoing endogenous alpha activity can influence awareness of visual targets, suggesting a pulsed inhibition of the sensory processing generated by alpha oscillations (Mathewson, Gratton, Fabiani, Beck, & Ro, 2009 ; Mathewson et al. 2011) which may interfere with ongoing visual/attentional processing (Mathewson et al., 2012; Spaak et al., 2014). Therefore, the alpha band might have a special place in SSVEP correlates of sensory perception.

Despite the robustness of the SSVEP, to our knowledge, it has not been evaluated in the study of temporal attention. This seems important to demonstrate, in part for use in fundamental science, and in part because temporal attention and the use of temporal cues to guide behavior is impaired in older adults (Zanto et al., 2011) and in clinical disorders including Parkinson's disease (Rochester et al., 2005; Tagliati, Bodis-Wollner, & Yahr, 1996) and schizophrenia (Liotti, Dazzi, & Umiltà, 1993; Nestor et al., 1992; Silberstein et al., 2000).

Thus, there were two goals to our study: First, to evaluate whether the SSVEP and its temporal dynamics can be used to study temporal attention; second, to evaluate whether attention-modulation of the SSVEP is similar for three different visual flicker frequencies (6 Hz, 10 Hz and 15 Hz). We selected 10 Hz flicker because it is the center of the alpha band and because, as described above, alpha oscillations seem to play a prominent role in temporal attention (Rohenkohl & Nobre, 2011). We then used two additional frequencies outside the alpha band range partly as control conditions for the alpha flicker, and partly to explore whether SSVEP amplitude would correlate with temporal attention for different stimulus frequencies. Therefore we selected the 6 Hz and 15 Hz.

To this end, we implemented a modified version of a task design by Mathewson et al. (2009), in which subjects reported whether they perceived a dim gray stimulus ("target") that was briefly flashed on a computer monitor. We manipulated the inter-stimulus interval (ISI) in different blocks to be either constant (ISIc - temporally predictable stimulus onsets) or variable (ISIv - temporally unpredictable stimulus onsets) (Woodrow, 1914). We predicted that in the ISIc compared to ISIv blocks, perceptual task performance would be improved and that EEG data would show increased SSVEP amplitude.

METHODS

Participants

30 subjects participated in the data collection. Data from two subjects were rejected due to poor behavioral performance. During EEG pre processing, the data of one subject were rejected due to excessive eye-blink artifacts in more than 30% of the trials and excessive lateral eye movements (i.e., left-right) at the time of target presentation. Finally, during the SSVEP analysis, data from two subjects were rejected due to an absence of visible SSVEP response in the power spectral plots. Thus, data from 25 participants (11 males, mean age 25.04, one left-handed) were included in the final analysis. All subjects had normal or corrected-to-normal vision. The study was conducted in accordance with the Declaration of Helsinki, relevant laws, and institutional guidelines, and was approved by the local ethics

committee at the Psychology Department at the University of Amsterdam. Participants signed an informed consent document prior to the beginning of the experiment and they were paid for their participation.

Task

Our task was designed to assess visual target detection performance with ISIc or ISIv. Participants were seated at a distance of approximately 90 cm from and at eye level of a 24" BenQ® monitor (1920 x 1080 pixels) with a refresh rate of 120 Hz. Stimulus presentation and behavioral response collection were controlled by custom-written scripts in Matlab® (The Mathworks, Natick, Massachusetts) using the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997).

Participants were requested to fixate the center of the screen. At the start of each trial, a circle (approximately 1.87° of visual angle; note that all measurements here are approximate because subjects were not restrained by, e.g., a chin rest) was presented in the position of the fixation cross (.47°) for 100 ms. Subjects were asked to press the left-mouse button if they saw a complete black circle or the right-mouse button if they saw a smaller gray circle (0.93° of visual angle; a "target") in the center of the black one. We call trials "target present" when the small circle was presented. This response mapping was not counterbalanced across subjects, although our primary analyses were not based on motor response hand. Subjects were instructed to respond as quickly and accurately as possible after stimulus presentation and they did not receive feedback regarding their performance. Figure 3.1 shows the stimulus features and the timeline of a trial sequence presented to each participant.

Surrounding the fixation and target stimulus was a black task-irrelevant rectangle (22.50° x 17.40° of visual angle) placed at 11.43° of visual angle from the top of the screen (Figure 3.1a,b). The rectangle was presented asymmetrically because this arrangement increases SSVEP amplitude by decreasing the possibility of electrical field cancellation across the calcerine sulcus (Vanegas, Blangero, & Kelly, 2013). Both the rectangle and the fixation cross were presented continuously throughout each block. In each block, the rectangle flickered in a specific frequency (6, 10, or 15 Hz). Square-wave time series were created for each frequency (50% on per frequency). Furthermore, in different blocks, the ISI was either constant at 1200 ms or variable, between 800 and 1600 ms with a mean of 1200 ms (ISI on each trial was drawn from a uniform distribution and participants were not informed about the different ISIs used in the task). These two independent manipulations produced six distinct block types, and each block type was presented twice. Thus, each subject completed 12 blocks, each comprising 124 trials and lasting approximately 2.5 minutes. Self-paced rest breaks were given between blocks.

The flickering frequency of the rectangle and the ISI were presented in pseudo-randomized order with the restriction that two consecutive blocks could not have the same flicker frequency. Targets were presented in 50% of the trials on each block. Subjects were verbally and visually instructed and performed a practice block of 124 trials before starting the actual experimental session.

The color-changing titration procedure was calculated based on target-present trials performance.

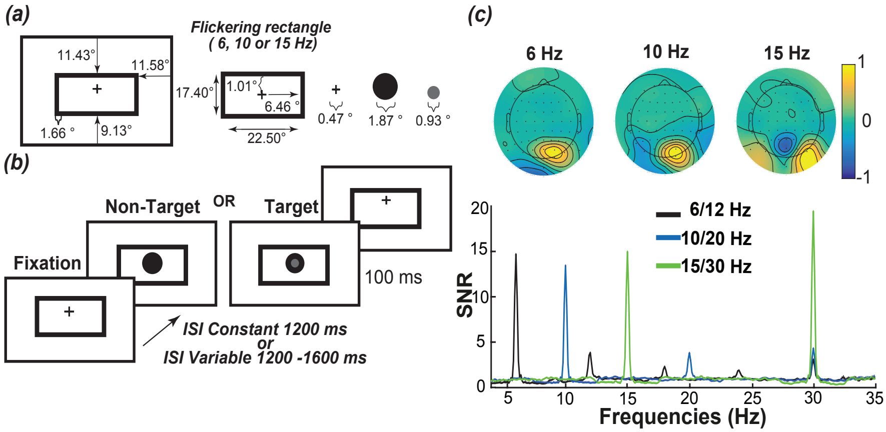


Figure 3.1. Stimulus features and time line of a trial sequence implemented to evaluate temporal attention (**a**). Individual features (e.g., spatial dimensions and flickering rate) of the stimuli presented on the screen. (**b**). Individual time line presentation of one trial. Note that flickering rate of the frame, ISI and presentation of the target and non-target was counterbalanced. (**c**). Topographical maps and power spectra from participant 17 as illustration. Top panel represents the RESS topographical maps for the frequencies used in our experiment showing higher SNR. Bottom panel shows the corresponding power spectrum at the corresponding fundamental frequency (6, 10, 15Hz) and the second harmonic (12, 20, 30 Hz).

Behavioral data analysis

Trials with RTs faster than 150 ms or slower than 2.5 standard deviations of the mean per condition and all error trials were excluded from the behavioral analysis. The statistical analyses of the 12 obtained conditions were performed using the statistical software SPSS® 22.0 (SPSS, Chicago, IL). The analyses for differences between conditions were tested using repeated measures analyses of variance (ANOVA) with factors: frequency, ISI and target, with the corresponding values 6, 10 and 15 Hz, constant and variable, and target present and target absent, respectively. Behavioral responses for accuracy were classified as hits, misses or false alarms. Hit responses were defined as the response within the defined time window for RTs and when the target was displayed. Responses given within the time window and reported as a target when it was not displayed were defined as false alarms. We primarily analyzed *d'*, a signal-detection-theory measure of discriminability. *d'* was quantified as $z(p_h)$-$z(p_f)$, where p_h and p_f are the probabilities of hits and false alarms, and $z()$ indicates the conversion from probability to standard deviation unit.

When appropriate, to compensate in case of violation of sphericity significance levels were adjusted using the Greenhouse-Geisser correction when performing repeated measures analyses of variance (ANOVA) and all the effect sizes are reported as partial eta squared (η_p^2) or Cohen's *d.*

EEG recordings and preprocessing

The EEG data were recorded with a sampling rate of 1024 Hz from 64 scalp electrodes. Two additional electrodes were placed in the outer canthi of each eye to measure horizontal eye movements (HEOG). All data were collected using a BioSemi® Active Two system (see www.biosemi.com for details). Data were preprocessed with the EEGLAB toolbox for Matlab (Delorme & Makeig, 2004).

The data were high-pass filtered offline at 0.5 Hz and re-referenced off-line to the scalp average. After baseline subtraction (−200 to 0 milliseconds pre stimulus baseline), trials with muscle and blinking artifacts during the stimulus were visually identified and manually removed (average of 9%). Then, additional artifacts or any other kind of noise not related to brain activity were removed using independent component analysis in EEGLAB (Delorme & Makeig, 2004). Additionally, although the EEG analysis was performed using the RESS filter we initially applied the Laplacian transform in all the data in order to improve the spatial selectivity of the data (Cohen, 2014). However, the Laplacian transform has minimal effect in the SSVEP SNR (Cohen & Gulbinaite, 2017) and the results did not qualitatively differ with or without the Laplacian. All EEG analyses involved only correct trials.

SSVEP analyses

We performed two sets of analyses on the SSVEP data for both the fundamental frequency and the second harmonic response: "static SSVEP," in which the Fourier transform was computed over the time window of interest from -600 to 600 ms, and "dynamic SSVEP," in which a narrow band-pass Gaussian filter was applied to inspect time-varying changes in SSVEP amplitude. Whereas the former method provides higher frequency resolution and increases signal-to-noise characteristics, the latter method provides higher temporal precision and thus the ability to detect time-varying changes in SSVEP amplitude resulting from phasic task events. The time windows for analysis were selected after visual inspection of pilot data, and were applied equally to all conditions.

SSVEP was extracted using a spatial filtering method termed rhythmic entrainment source separation (RESS; Cohen & Gulbinaite, 2017). The basic assumption is to create linear spatial filters that then multiply the EEG electrode time series data to produce a single RESS component per frequency. These components are then analyzed instead of analyze the data from each electrode. The RESS method involves using generalized eigendecomposition to construct an optimal spatial filter that maximizes the SSVEP effect. The eigenvector with the largest eigenvalue maximally differentiates two covariance matrices (a "signal" and a "reference" covariance matrix), and that vector is used as channel weights to combine data from all electrodes. The signal covariance matrix was obtained from the narrowband filtered data at each stimulus frequency and its second harmonics. The reference covariance matrix was obtained from data filtered at the closely spaced up and down-neighbor frequencies. Constructing the reference matrix in this way provides accurate SSVEP time course reconstruction. Similarly, because neural responses are topographically and anatomically different compared to responses at the fundamental frequency, implementing RESS to separate SSVEP harmonics reduces possible confounding effects induced due to muscle artifacts, particularly at temporal and frontal electrodes. More details about temporal filtering and the RESS method are presented in Cohen & Gulbinaite (2017). Importantly, the spatial filters were computed per frequency pooling data across all conditions separately for each participant; thus, although the spatial filter maximizes the overall SSVEP amplitude, there is no potential for biasing any condition comparisons. The power spectrum was computed via the fast-Fourier transform for each flicker condition (6, 10 and 15 Hz) pooling over ISI and target conditions, in the time window from -600 ms to 600 ms peri stimulus onset. First we computed the FFT separately for each trial, and then averaged the power spectra over trials per condition. The static SSVEP was computed as signal-to-noise ratio (SNR) as the ratio of the power at the flickered frequency to the average of neighboring frequencies surrounding each frequency (+/- 2 Hz, excluding a .5 Hz window around each center frequency) allowing to convert power spectrum into SNR units to facilitate comparability across groups (Figure 3.1c). Additionally, we computed the SNR per condition to look for differences between the ISIc and ISIv conditions. The SNR was computed for correct trials pooled over target conditions and defined by frequency and ISI with the corresponding values of 6, 10 and 15 Hz and constant and variable ISI, respectively, using a sliding trial window that included 18 trials on either side of the current trials, thus having a running average of 37 trials. This trial series was then interpolated to 200 units in order to average across subjects with different trial counts.

For the computation of the dynamic SSVEP amplitudes, a narrow-band Gaussian filter was implemented for each of the flicker conditions (6, 10 and 15 Hz) with a full width at half-maximum (FWHM) of 3 Hz (the standard deviation of the filter). This Gaussian was point-wise multiplied by the power spectrum of the EEG data, and the inverse Fourier transform was applied to reconstruct the time course of the activity (i.e., convolution). After filtering the data, the amplitude of the frequencies of interest was extracted as the squared magnitude of the result of the Hilbert transform. We call this time series the “SSVEP time series.” To facilitate comparisons across subjects, the SSVEP time series was baseline-normalized to a pre stimulus period of -600 to -200 ms, separately for each frequency. Because in our task the flicker stimulus was present all the time, including the peri-stimulus period, the baseline was computed based on the average of all conditions within each frequency, thus allowing for detection of possible condition differences in pre stimulus activity. Baseline normalization allows rescaling the activity relative to the selected baseline, which facilitates comparison between frequencies (Cohen, 2014).

Our analyses were focused on the static (e.g., SNR) and dynamic (e.g., time-varying changes in amplitude) components of the SSVEP amplitude. Because the target onset was non phase-locked with respect to the flicker stimulus onsets, it was not possible to compute intertrial phase coherence (ITPC; Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1996). ITPC provides an amplitude-independent measure on how the stimulus EEG response is phase-locked to the stimulus dynamics (Kim et al., 2007). For example, Kim et al. (2007) concluded that ITPC showed attentional effects of the SSVEP phase-locking in response to changes in attended stimulus suggesting an increased synchronization of neural population.

SSVEP statistical analyses

The analyses for the SNR differences between conditions were tested using repeated measures ANOVA with factors: frequency (6 Hz, 10 Hz and 15 Hz), ISI (constant and variable) and target (present and target absent). In order to detect time-varying changes in SSVEP amplitude resulting from phasic task events, statistical analyses of the EEG SSVEP time series were implemented for the 12 experimental conditions (flicker, ISI and target) and for the 6 reorganized conditions pooled over target conditions and defined by frequency and ISI with the corresponding values of 6, 10 and 15 Hz and constant and variable ISI, respectively. Nonparametric permutation testing was used in combination with cluster correction to evaluate condition differences in dynamic SSVEP over time (Maris & Oostenveld, 2007). To create a distribution of null-hypothesis time courses, we computed the difference of ISIc – ISIv for each subject, and then multiplied this condition difference for a random subset of subjects by - 1 (which is equivalent to randomizing ISIv - ISIc vs. ISIc - ISIv). This was repeated for 1000 iterations. Finally, cluster correction was implemented to correct for multiple comparisons over the all-corresponding time points of the selected time window with a threshold value for pixel-and cluster-levels of $p = .05$.

Post hoc analyses for the second harmonics (12, 20 and 30 Hz) of the flickering stimulation was performed for the SNR and the dynamic SSVEP following the same parameters implemented for the fundamental frequencies.

RESULTS

Behavioral results

Table 3.1 lists all mean RTs and *d*’ values; here we report only significant ANOVA effects. For RTs, there were significant main effects for the ISI and target factors, such that subjects were faster to respond in blocks with ISIc compared to ISIv (M = 403.65 ms and M = 425.92 ms; $F(1,24) = 28.49$, $p < .001$, $\eta_p^2 = .543$), and target-present trials compared with target-absent trials (M = 406.02 ms M = 423.54 ms; $F(1,24) = 14.63$ $p = .001$, $\eta_p^2 = .379$) (Figure 3.2a).

There was no significant main effect of flicker frequency, nor any interactions involving this factor (all *p*’s > .1). Furthermore, interactions analysis between ISI and target factors did not reveal significant effects (all *p*’s > .1).

Table 3.1. Results from all experimental conditions.

Frequency (Hz)	ISI[a]	Target[b]	Reaction times (ms) Mean	*SD*	Accuracy (%) Mean	*SD*
Descriptive statistics						
6	C	P	397.52	71.48	85.18	3.18
	C	Ab	411.43	65.18	84.68	10.24
	V	P	414.90	67.44	84.75	3.31
	V	Ab	436.63	52.01	83.39	11.19
10	C	P	393.01	64.37	86.78	3.87
	C	Ab	407.30	57.61	86.41	11.48
	V	P	420.08	64.05	83.80	3.26
	V	Ab	441.34	61.00	83.11	10.27
15	C	P	398.21	68.20	85.35	4.34
	C	Ab	414.37	53.61	86.23	8.83
	V	P	412.39	70.62	84.95	3.47
	V	Ab	430.15	67.13	82.50	11.78

Variable	*df*	*F*	*P*[*]
Repeated measures ANOVA for reaction times			
Frequencies	2	0.130	.878
ISI	1	28.486	.000
Target	1	14.63	.001
Frequencies X ISI	2	2.367	.105
Frequencies X Target	2	0.015	.985
ISI X Target	1	1.756	.198
Frequencies X ISI X Target	2	0.219	.804
Repeated measures ANOVA for *d'*			
Frequencies	2	0.307	.737
ISI	1	5.998	.022
Frequencies X ISI	2	2.52	.091

Pair	Mean	*SD*	95% CI of the difference	*r*	*t*	*df*	Sig. (2-tailed)
Results of the t test and descriptive post hoc statistics for the reaction times							
All conditions 6 + 15 Hz All conditions 10 Hz	.77618	44.23	-17.48, 19.03	.60*	.088*	24	.931
All conditions 6 + 10 Hz All conditions 15 Hz	-1.6729	49.21	-21.97, 18.64	.60*	-.170*	24	.866
Results of the t test and descriptive post hoc statistics for the *d'*							
All conditions 6 + 15 Hz All conditions 10 Hz	.20429	.44045	.022, .386	.44*	2.31*	24	.029

Note: Upper table contains the descriptive statistics for RTs and accuracy for all the conditions. Middle tables contain the results of the ANOVA analysis performed for accuracy and *d'*, respectively. Bottom tables contain the results of the post hoc *t* test analysis performed for RTs and for *d'*. SS = sum of squares; MS = mean square.

[a] *C = constant, V: variable.*

[b] *P: present, Ab: absent. * p < .05*

Although there was no statistically significant interaction effect involving flicker frequency, we performed an additional post hoc analysis in which we compared RTs on target-present vs. target-absent trials for the 10 Hz condition compared to the average of 6 Hz and 15 Hz conditions. Paired-samples t-test showed no significant effects (all *p's* > .1) between conditions. Because the difference between ISIc and ISIv for the target absent conditions at 15 Hz is smaller than the difference between the 6 and 10 Hz for the ISIc vs. ISIv (Figure 3.2a) we evaluated whether the effect of temporal attention for the 15 Hz conditions was as strong as for the 6 and 10 Hz. Therefore we compared RTs on target-present vs. target-absent trials for the average of the 6 and 10 Hz conditions compared to the 15 Hz condition. Paired-samples t-test for showed no significant effects (all *p's* > .1) between conditions (See table 3.1).

For all conditions, accuracy was higher than 80%. Our analyses focused on *d'* because it is more sensitive for measuring discrimination performance compared to accuracy (statistics for accuracy are shown in Table 3.1). For all the flicker frequencies, trials with ISIc showed higher *d'* as compared with trials with ISIv (Figure 3.2b). A significant effect was found for ISI, meaning that participants were more accurate at detecting targets in trials with ISIc as compared with ISIv trials (M = 2.26 and M = 2.08; $F(1,24) = 5.99$, $p = .022$, $\eta_p^2 = .200$). Results for frequency flicker effect and the interaction between frequency and ISI did not reveal significant effects ($p > .1$).

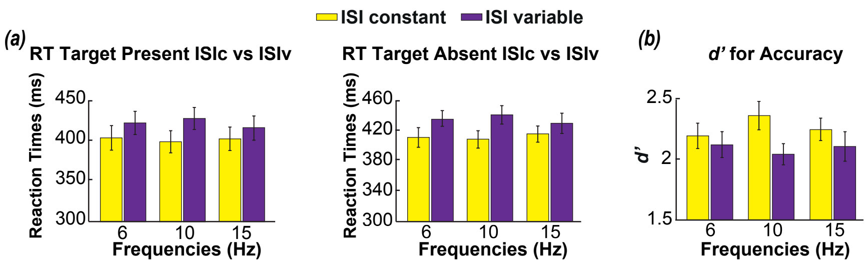


Figure 3.2. Behavioral results for the reaction times and *d'*. Error bars represent standard error of the mean. **(a).** Participants showed faster reaction times for conditions with ISI constant for both target present and target absent trials. This effect was similar for conditions at 10 Hz as compared with conditions where the flickering frequencies were either 6 or 15 Hz. **(b).** *d'* represents the probability of hits and false alarms converted to standard deviation units.

Follow-up t-tests (Table 3.1 bottom cell) revealed higher *d'* on ISIc and ISIv trials for the 10 Hz condition ($M = .3156$, $SD = .40344$) compared to the average of 6 Hz and 15 Hz conditions (6 and 15 Hz: $M = .1113$, $SD = .42962$; $t(24) = 2.31$, $p = .029$, d = 0.46). However, the ISI-by-frequency interaction term in the ANOVA was not significant, so this *t*-test result should be interpreted cautiously.

EEG results

SNR for fundamental frequencies

For all the flicker conditions and for all frequencies, the SNR spectrum exhibited peaks at the SSVEP frequencies as well as several higher harmonics (Jackson & Bolger, 2014), indicating that our experiment was sufficient to elicit robust SSVEP effects. Repeated-measures ANOVA (with factors: frequency, ISI and target – see *Method* section) for each of the experimental conditions showed a significant main effect for frequency ($F(2,48) = 12{,}06$, $p < .001$, $\eta_p^2 = .335$), and interaction effects for ISI x target ($F(1,24) = 7.24$, $p = .013$, $\eta_p^2 = .232$) and target x frequency ($F(2,48) = 3.69$, $p = .032$, $\eta_p^2 = 133$). The frequency x ISI and ISI x target x frequency interactions showed significant effects but reported violation of sphericity in the Mauchly's test: $X^2(2) = 6.99$, $p = .030$ and $X^2(2) = 14.45$, $p = .001$, respectively. Therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for the ISI x frequency ($\varepsilon = .792$, $F(1.58, 38.02) = 4.52$, $p = .024$, $\eta_p^2 = .159$) and the ISI x target x frequency ($\varepsilon = .684$, $F(1.38, 32.84) = 3.32$, $p = .045$, $\eta_p^2 = .121$). However, the main effect of ISI was not statistically significant ($F(1,24) = 0.40$, $p = .533$, $\eta_p^2 = .016$), indicating that there were no generic effects of temporal expectations across all SSVEP frequencies. Figure 3.3a shows the SNR for the experimental conditions at the fundamental frequency. The bar plots show (1) higher SNRs for 10 Hz and 15 Hz compared to 6 Hz, and (2) the lack of a main effect of ISI condition. Figure 3.3c (left panel) shows the topographical distribution of the forward model of the RESS spatial filter averaged over all participants, targets and ISI conditions with maximum response at posterior central electrodes. Table 3.1S in the supplement contains all the ANOVA results for the fundamental frequencies.

SNR for the second harmonic

Given the robust harmonic SSVEP power in our data (e.g., Figure 3.1c), we conducted additional exploratory (post hoc) tests to determine whether the second SSVEP harmonic response might be a better marker of temporal expectations. Results of repeated-measures ANOVA (with factors: frequency, ISI and target – see *Method* section) for the second harmonics (12Hz, 20Hz, 30Hz) showed significant effects for the flicker-frequency factor ($F(2,48) = 10.1$, $p < .001$, $\eta_p^2 = .296$) and for the interaction between ISI and target factor ($F(1,24) = 4.93$, $p = .036$, $\eta_p^2 = .170$). We also obtained a marginally significant interaction between ISI and frequency but the Mauchly's test showed violation of sphericity $X^2(2) = .708$, $p = .002$. After correcting the degrees of freedom using Greenhouse-Geisser estimates of sphericity the effect was not significant ($\varepsilon = .708$, $F(1.41, 33.97) = 2.71$, $p = .097$, $\eta_p^2 = .101$). Again, there was no main effect of ISI condition ($F(1,24) = 1.47$, $p = .199$, $\eta_p^2 = .068$). Figure 3.3b shows bar plots of the SNRs for the second harmonic.

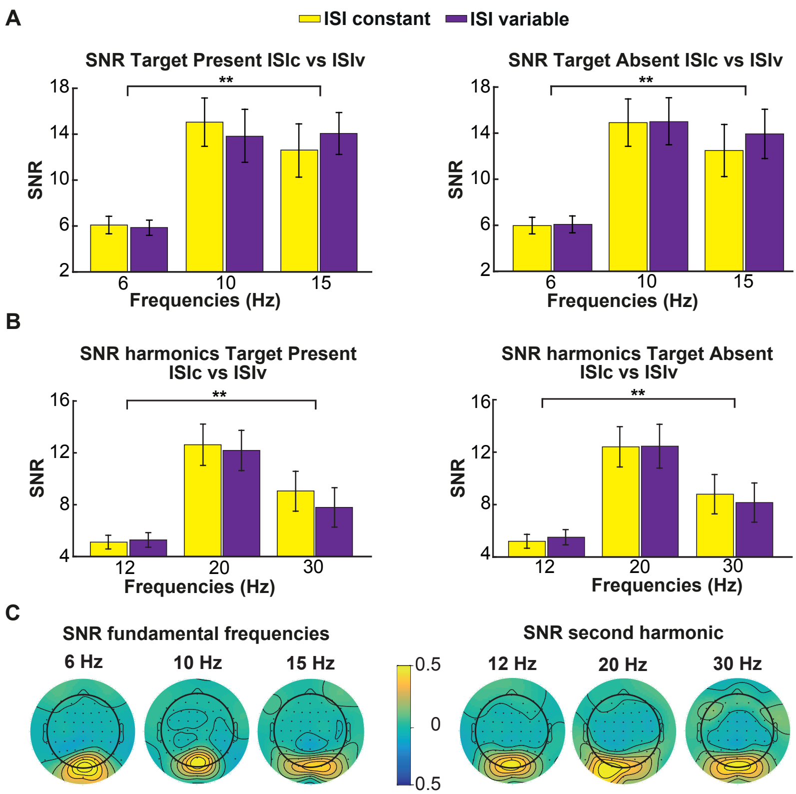


Figure 3.3. Average SNRs per experimental condition. **(a)**. SNR values for the fundamental frequencies (6Hz, 10Hz and 15Hz) for target present (left) and target absent conditions (right) between ISIc vs. ISIv. **(b)**. SNRs obtained from the second harmonics (12Hz, 20Hz and 30Hz) of the flicker stimuli. Arrangement of target and ISI factors in panel (b) is the same as in (a). **(c)**. Topographical maps of subject average for the SNRs for the fundamental frequencies (left) and the second harmonics (right). Values in the y-axis correspond to converting power spectrum to SNR units. Error bars represent standard error of the mean. ** = $p < .01$

The bar plots show (1) similar SNR differences between 20 Hz and 30 Hz compared to 12 Hz, (2) the lack of a main effect of the ISI condition as observed in panel a, and (3) higher SNR for the 20 Hz compared to the 12 Hz and 30 Hz. Figure 3.3c shows the topographical distribution of the forward model of the RESS spatial filter at the second harmonics (right) averaged over all participants, targets and ISI conditions with maximum response at posterior central electrodes. Table 3.1S in the supplement contains all the ANOVA results for the second harmonic.

SNR across trials per condition

To determine whether attention-modulated SSVEP amplitude might have been present only later during the experimental blocks, we computed SNR over sliding trial-windows per condition, and averaged “early” (first third) vs. “late” (last third) of trials in each block. We performed repeated-measures ANOVA with factors: trials position (early vs. late), ISI (constant vs. variable) and frequency (6, 10 and 15 Hz). Significant main effects were obtained only for the frequency factor ($F(2,48)$ = 11,35, $p < .001$, η_p^2 = .000). The interaction between Frequency x ISI showed significant effects but reported violation of sphericity in the Mauchly's test: $X^2(2)$ = 10.82, p = .004, therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .727, $F(1.45, 34.90)$=3.45, p = .056, η_p^2 = .126), producing a non significant effect. However, the main effect of ISI ($F(1,24)$ = 0.92, p = .764), trial position ($F(1,24)$ = 0.002, p = .967) and trial position x ISI interaction ($F(1,24)$ = 1.28, p = .268) were not significant. Figure 3.4 shows the SNR across trials for each of the flickering conditions for the two ISI factors. For the 6 Hz, ISIc condition the SNR was constantly higher as compared to the ISIv conditions. Similar SNR effects can be observed for the 10 Hz, ISIc condition as compared to the ISIv condition. However, it can be observed that for the 10 Hz flicker there is an "inverse" effect between the ISIc and ISIv for trials around mid block. And for the 15 Hz the changes in the SNR are higher for the ISIv as compared with the ISIc.

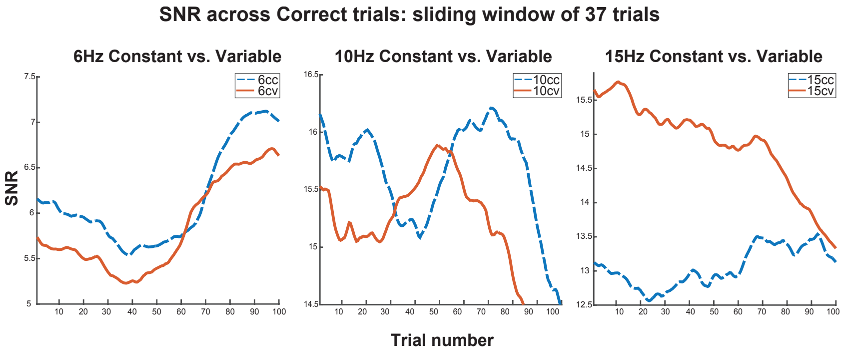


Figure 3.4. Differences between the ISIc vs. ISIv conditions for the SNR values across trials for the 6, 10 and 15 Hz. Values in the y-axis correspond to converting power spectrum to SNR units.

Dynamic SSVEP results for fundamental frequencies

To analyze SSVEP changes in amplitude across time all correct trials were pooled over target condition and separated according to frequency and ISI factors. For the 6 Hz and 10 Hz flickering conditions a significant change in amplitude was observed for conditions with ISIc as compared with ISIv conditions (all p values < .05, cluster-corrected for multiple correlated tests over time points). These effects were observed for the time interval between 68 ms and 205 ms for the 6 Hz and 123 ms to 301 ms after target presentation for the 10 Hz flicker condition. An opposite effect was observed for the 15 Hz flicker condition where trials with ISIv showed positive significant changes in amplitude relative to the baseline as compared with the ISIc trials. And this difference in amplitude was significant for the complete analyzed time window (p < .05). Figure 3.5a shows the results of the nonparametric permutation testing that was used in combination with cluster correction to evaluate condition differences in dynamic SSVEP over time for correct trials.

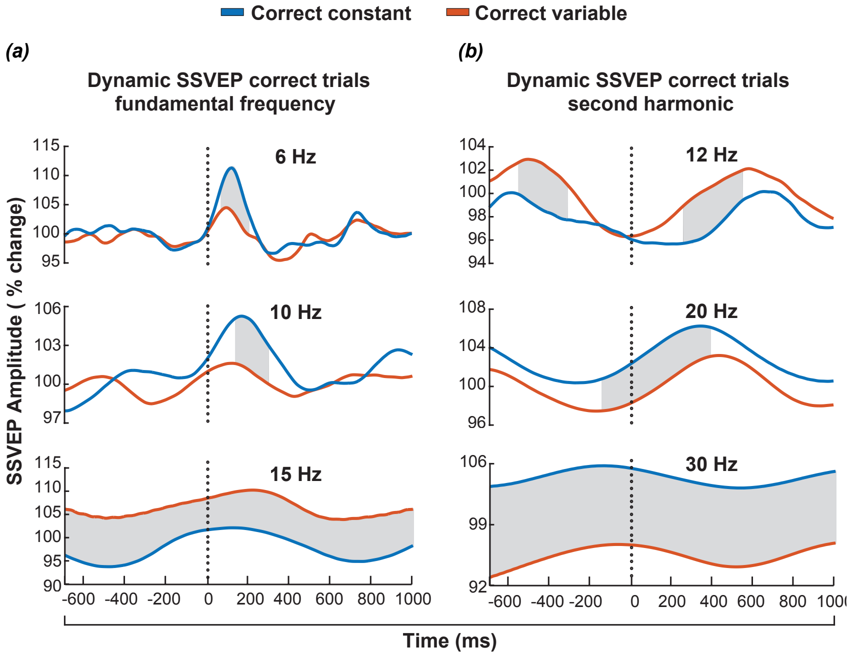


Figure 3.5. SSVEP time course amplitudes for correct trials pooled over target conditions for correct ISIc vs. correct ISIv trials. SSVEP time series were baseline-normalized to a pre stimulus period of -600 to -200 ms. SSVEP percentage change amplitudes for **(a)** the fundamental frequencies (6 Hz, 10 Hz and 15 Hz), and **(b)** the second harmonic (12 Hz, 20 Hz and 30 Hz). Dotted line at time 0 represents stimulus presentation. Grey areas represent statistically significant differences between ISI-constant and ISI-variable conditions (p < .05).

Dynamic SSVEP results for the second harmonic

As with the static SSVEP, we conducted a post hoc analysis to determine whether the second harmonic might be a more robust indicator of temporal attention. The second harmonic of the 6 Hz flicker (12 Hz) showed increase in the SSVEP amplitude for trials with ISIv as compared with conditions with ISIc. This “reversed effect” was significant for the time windows between -550 ms to -326 ms, before target presentation, and between 226 ms and 547 ms, after target presentation (p < .05). For the harmonics at 20 Hz and 30 Hz the change in amplitude was larger for ISIc trials vs. ISIv trials. The 20 Hz showed a significant difference for the time window between -142 ms to 390 ms. And for the harmonic at 30 Hz the difference was significant for the entire time window as observed for the fundamental frequency (15 Hz). However, this effect in the second harmonic (30 Hz) was opposite to the fundamental frequency being higher for conditions with ISIc. Figure 3.5b shows the results of the dynamic analysis for the second harmonics.

DISCUSSION

SSVEP and temporal attention

In this study we evaluated whether the SSVEP and its temporal dynamics could be used to study temporal attention, and whether the effects of attention modulation were similar for the 6 Hz, 10 Hz and 15 Hz SSVEP stimuli. We designed an SSVEP-temporal attention task where temporal expectations were induced by manipulating duration of intervals between ISIs while participants differentially responded between a target and non-target visual stimulus. We found that the amplitude of the SSVEP was significantly increased for the fundamental frequencies at 6 Hz and 10 Hz in blocks with ISIc compared to ISIv blocks. Similar effects were observed for the second harmonic of the alpha-band stimulus (20 Hz) for blocks with ISIc.

To our knowledge, this is the first study evaluating the applicability of SSVEP in temporal attention. The behavioral evidence showed significant improvement for the ISIc vs ISIv condition, which confirmed strong temporal expectations effects in our experiment. The SSVEP effects, however, were not as strong as expected, and we cannot conclude that SSVEP is universally appropriate for EEG studies of temporal attention. On the other hand, several of our results support the use of SSVEP in some cases, particularly in the alpha-band range for the fundamental and the second harmonic. Hence, the SSVEP may provide a feasible tool to study temporal attention if used carefully.

It is possible that the effects would have been stronger if the flicker had been presented foveally or were task-relevant. On the other hand, the overall SSVEPs had high SNR (e.g., Figures 3.1 and 3.3), and task-relevance is not a prerequisite for attention modulations in spatial and object-based attention tasks (Müller et al., 2006; Senkowski et al., 2008). Similarly, in our experimental design we use rhythmic cues to induce temporal expectations. An important for future research is to determine whether more robust effects would be obtained with different methods of inducing temporal expectations (e.g., instructive/predictive cues). Given that different ways of inducing temporal expectations could activate different neurophysiological mechanisms (Rohenkohl et al., 2014), using alternative ways to induce temporal expectancies (e.g., Coull & Nobre, 1998; Cravo, Rohenkohl, Wyart, & Nobre, 2011; Graaf et al., 2013) in future SSVEP-temporal attention paradigms might improve the effects on SSVEP. . Additionally, it is possible that a different design that allows for ITPC analysis may provide additional insights into whether and how SSVEP could be useful for studying temporal attention. Again, although we would not rule out the potential utility of the SSVEP technique for studying temporal attention, such studies may require carefully selected stimulus parameters and experiment design choices.

SSVEP and attention

The SSVEP has extensively been used to study sensory (Regan, 1989) and visual processes (Norcia et al., 2015) and particularly it has been used to study attentional processing (e.g., Morgan et al., 1996; Pei, Pettet, & Norcia, 2002). And the increased amplitude of the SSVEP for the attended as compared to the unattended conditions has been replicated many times (Andersen & Müller, 2010; Kashiwase et al., 2012; Kim et al., 2007; Morgan et al., 1996; Müller et al., 2006; Saupe et al., 2009). However, these studies have focused on spatial or object attention, and it thus remained unclear whether SSVEP would also be useful for studying the dynamics of temporal attention. Our results are in line with previous reports in the sense that we found possible temporal attention-modulation on SSVEP. Nonetheless, it is important to stress that in our temporal expectations paradigm this effect on SSVEP was not observed for 15 Hz flicker.

Our results also showed changes in the amplitude of the second harmonic for the 20 Hz and 30 Hz, which could be related to the effects of temporal expectancy induced by the ISIc. Nonetheless, changes in amplitude of the second harmonic at 12 Hz were for the ISIv condition. Again, because our study is the first to evaluate the use of the SSVEP to study temporal attention, the inverse effect on the 12 Hz second harmonic should be confirmed in futures studies before giving potential explanations related with neural mechanisms of temporal attention. And one approach to further evaluate our results would be examining the ITPC. It has been previously shown that ITPC provides a measure of the phase consistency of EEG responses to stimulus dynamics (Kim et al., 2007). However, our results for the second harmonics are consistent with previous reports describing the effects of attention modulation of the SSVEP second harmonic (Belmonte, 1998; Müller, Picton, et al., 1998; Pei et al., 2002; see Norcia et al., 2015 for a review).

Relation to motor processing

Some studies have suggested that behavioral effects could be better explained by motor effects in a temporal attention task (Correa & Nobre, 2008; Davranche et al., 2011). In order to isolate the motor-related activity including any possible effects induced by the response mapping we implemented, we designed a forced-choice perceptual task where the motor response was not requested until stimulus presentation. In this way the motor effect could be attributed to separate effects presented at the level of the motor cortex (Rohenkohl & Nobre, 2011) confirming the improvement in behavioral performance as result of temporal expectations induced by rhythmic intervals. This seems relevant because temporal attention involves more processes than motor preparation or holding motor responses (Coull et al., 2000).

CONCLUSIONS

Part of the interest of determining whether SSVEPs can be useful for studying temporal attention are for potential applications in clinical research, in particular in conditions associated with impairments in orienting attention in time or the use of temporal cues to improve performance, such as Parkinson's disease (Rochester et al., 2005; Tagliati et al., 1996) and schizophrenia (Liotti et al., 1993; Nestor et al., 1992; Silberstein et al., 2000). SSVEPs for temporal attention could also be relevant for studying changes in healthy aging, because changes in temporal attention have also been reported in this population (Zanto et al., 2011; Zanto, Hennigan, Mattias, Clapp, & Gazzaley, 2010), and SSVEPs for spatial/object attention have already been employed to study changes in attention in aging (see Vialatte et al., 2010 for a review).

Despite the theoretical and practical relevance of using SSVEP to study temporal attention, our results provide some behavioral and EEG evidence to show the feasibility of the SSVEP to study temporal attention and the effects of temporal predictability on SSVEP. However, we must highlight that this was observed in our experiment mainly for the 6 Hz and 10 Hz and not for the 15 Hz flicker frequency. Further research will be required to determine how to optimize stimulus and experiment design parameters for using SSVEP to study temporal attention.

ACKNOWLEDGEMENTS

We thank Dr. Rasa Gulbinaite for advice on the experiment design.
A. M. C. is funded by Departamento Administrativo de Ciencia, Tecnología e Innovación, Colciencias call 529/ 2011 (Colombia). M. X. C. is funded by an ERC-StG 638589.

DECLARATION OF INTEREST STATEMENT

The authors declare that there are no conflicts of interests.

AUTHOR CONTRIBUTIONS

M.X.C. conception and design of research and analysed data; A.M.C. performed experiments; analysed data; M.X.C. and A.M.C. interpreted results of experiments; A.M.C. prepared figures; drafted manuscript; A.M.C., M.X.C. and R.K.R. edited and revised manuscript; M.X.C. and R.K.R. approved final version of manuscript.

SUPPLEMENT SSVEP AND TEMPORAL ATTENTION

Table 3.1S. SNR results for the fundamental frequency and the second harmonic. Upper table contains the ANOVA analysis performed for the fundamental frequency. The table at the bottom contains ANOVA analysis performed for the second harmonic.

Variable	*df*	*F*	*p**	*ε ***
Repeated measures ANOVA SNR for fundamental frequencies				
Frequencies	2	12.06	.000	.000
ISI	1	.40	.533	.533
Target	1	1.42	.246	.246
Frequencies*ISI	2	4.52	.016	.024
Frequencies*target	2	3.69	.032	.039
ISI*Target	1	7.24	.013	.013
Frequencies*ISI*target	2	3.32	.045	.065

Variable	*df*	*F*	*p**	*ε ***
Repeated measures ANOVA SNR for second harmonic				
Frequencies	2	10.09	.000	.000
ISI	1	1.75	.199	.199
Target	1	.42	.521	.521
Frequencies*ISI	2	2.71	.077	.097
Frequencies*target	2	.49	.616	.609
ISI*Target	1	4.93	.036	0.36
Frequencies*ISI*target	2	1.55	.222	.225

**p < .05, ** ε = Epsilon Greenhouse-Geisser correction.*

Chapter 4

Using the SSVEP to measure the SNARC-spatial attention effects in a parity judgment task

ABSTRACT

Mental representation of numbers in the brain has been described as spatially organized on what is known as the "mental number line," with small numbers to the left and large numbers to the right. This representation leads to the "SNARC effect" (Spatial-Numerical Association of Response Codes), which refers to (1) improved behavioral performance for "congruent" conditions (e.g. left-handed response to small numbers) as compared to "incongruent" conditions (e.g. right-handed response to small numbers) and (2) perceiving numbers induces an automatic shift in covert spatial attention. Nonetheless, there is scarce physiological evidence for (or against) the prediction that number magnitude induces an automatic shift of spatial attention. Here we recorded EEG during the bimanual SNARC-parity judgment task (classifying numbers as odd or even) in attempt to find electrophysiological evidence for number-magnitude-induced automatic shifts of spatial attention. Attention was measured using the SSVEP (steady-state visual evoked potential) from four task-irrelevant flickering frequencies (two to the left: 15 and 20 Hz and two to the right: 24 and 17.14 Hz) in combination with an optimal spatial filtering method. EEG analysis was performed on the flicker frequencies closest to the fixation point: 20 and 24 Hz for the left and right visual hemifields, respectively. We replicated the expected behavioral patterns predicted by the SNARC effect, such that participants performed better for congruent conditions than on incongruent conditions. We observed significant changes in the SSVEP amplitude with respect to the baseline for the left (20 Hz) and right (24 Hz) flicker for both the congruent and incongruent conditions. Statistically significant differences between the congruent and incongruent conditions were larger for the congruent conditions for the flicker stimuli on the left. Together, these findings support the hypothesis that when numbers are part of the task but their magnitude is not relevant, the SNARC-spatial attention effect is elicited as a cognitive effect resulting from the mental representation of numbers and its relation with the space representation, more than merely a motor effect.

Keywords: SNARC, spatial attention, parity judgment, SSVEP

Based on*: Mora-Cortes, A., Gulbinaite, R., Ridderinkhof, K.R., Cohen, MX. Numbers, the where of spatial attention and the SSVEP. Manuscript under preparation.*

INTRODUCTION

Modern human innovations and advanced thinking like math and science have numbers as their cornerstone. Therefore, understanding how numbers are represented in the brain is a crucial topic for understanding human cognition and intelligence. An intriguing insight into the neural representation of numbers comes from the observation that numbers seem to be mentally represented on a so-called mental number line (MNL), where numbers are organized according to their increasing magnitude (Moyer & Landauer, 1967; Restle, 1970) (See Figure 4.1).

Following this idea, Dehaene, Bossini & Giraux (1993) showed for the first time that numbers seem to be spatially represented in a horizontal MNL with a specific direction going from left-to-right according to number sign and magnitude. This means that small magnitude numbers like “1” or “2” are associated with the left side of space while large magnitude digits like “8” or “9” are associated with the right side of the space. The authors used the parity judgment task (classify odd vs. even numbers) across different experiments using different response mappings (e.g., even-left vs. odd-right, bimanual parity judgment) and concluded that participants were faster to respond to small-magnitude numbers, and slower to respond to large-magnitude numbers, with the left hand, and vice-versa for the right hand. The authors termed this the Spatial-Numerical Association of Response Codes (SNARC) effect. The SNARC effect is present not only when the number magnitude is relevant for the task (magnitude-judgment) but also when the magnitude information is not relevant (parity judgment; Fias & Fischer, 2004; Fias, Lauwereyns, & Lammertyn, 2001).

Although the SNARC effect was described in a bimanual response task, it has also been reported in pointing tasks (Fischer, 2003), eye-movements (Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004), grasping (Andres, Ostry, Nicol, & Paus, 2008), verbal (Keus & Schwarz, 2005), and bipedal responses (Schwarz & Müller, 2006). Similarly, it has been shown that the SNARC effect is present in non-numerical tasks such as phoneme detection for digits’ names (Fias, Brysbaert, Geypens, & d’Ydewalle, 1996), and midpoint localization on long strings of numbers (Fischer, 2001). These studies show that the SNARC effect is a fundamental representation and is not linked to one particular response modality or experiment paradigm.

Supporting the notion that SNARC reflects the mental representation of numbers magnitude in this left-to-right spatial organization, it has been reported that perceiving numbers induces an *automatic shift of spatial attention* to the left when small numbers are observed and towards the right side of space when large numbers are perceived (Fischer et al., 2003). However, there have been difficulties in replicating the modulation of spatial attention induced solely by the mere observation of numbers, as described by Fischer, making its reliability difficult to ascertain.

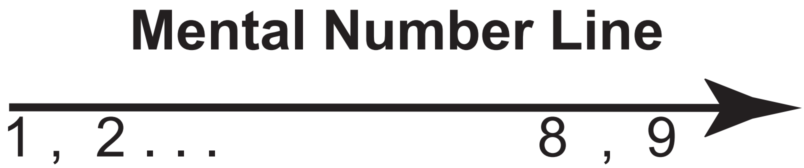


Figure 4.1. Sketch of number representation according to the MNL where small numbers (e.g., 1 and 2) are spatially represented to the left side and large numbers (e.g., 8 and 9) on the right side of the MNL.

On the one hand, several follow-up studies have replicated the SNARC effect (i.e., in parity or magnitude judgment tasks) and authors have claimed that it is explained by the MNL theory (Chinello, de Hevia, Geraci, & Girelli, 2012; Göbel, Calabria, Farnè, & Rossetti, 2006; Hesse & Bremmer, 2017; Müller & Schwarz, 2007; Schwarz & Keus, 2004; Shaki, Fischer, & Göbel, 2012; Weis, Estner, van Leeuwen, & Lachmann, 2016; Zohar-shai et al., 2017; Zorzi, Priftis, & Umiltà, 2002; See Fias & Fischer, 2005 for an extended review), while some others have proposed that the SNARC effect could be better explained by the stimulus response compatibility (SRC; Fitts & Seeger, 1953; Kornblum, Hasbroucq, & Osman, 1990), the dual-route cognitive model (Gevers et al., 2005; Gevers, Ratinckx, et al., 2006) or the polarity correspondence theory (PCT) of compatibility (Proctor & Cho, 2006). Results from fMRI (Pinel et al., 2004; Vogel, Grabner, Schneider, Siegler, & Ansari, 2013) and ERP studies (Gut et al., 2012; Keus, Jenks, & Schwarz, 2005) have supported this response target-stimulus related notion of the SNARC effect.

On the other hand, the spatial SNARC-spatial attention effect (to differentiate it from the classical SNARC effect observed in motor responses during parity or magnitude task) as described by Fischer et al. (2003) has been elusive to reproduce. While some authors have replicated the SNARC-spatial attention (Galfano et al., 2006; Ristic et al., 2006) claiming that this is not due to an automatic effect induced by numbers, other studies have failed to reproduce this SNARC-spatial attention effect (van Dijck, Abrahamse, Acar, Ketels, & Fias, 2014; Zanolie & Pecher, 2014).

This variability in the reported results suggest that mental representation of numbers, and that to elucidate the effect of numbers on allocation of spatial attention requires a direct measurement of attention while performing a task involving numbers. And despite the extended literature about the SNARC effect and the possible relation with allocation of spatial attention, most of the ERP or fMRI studies have focused on describing how numbers and mental representation of space interact to improve behavioral performance.

Similarly, some other studies have focused on explaining the cognitive components that would support such interaction between numbers and space inducing the SNARC effect. Nevertheless, in the SNARC literature there is a lack of evidence regarding the direct measure of spatial attention while performing a SNARC task. Therefore, in order to better understand whether numbers have a direct effect in allocating spatial attention either when it is explicitly or implicitly manipulated, direct brain measurements (as opposed to indirect behavioral measurements) may provide more insight if numbers are processed by our brain as cues for stimulus-driven spatial attention. Thus, to provide physiological evidence of the effect of numbers on spatial attention, and to test if the implicit manipulation of spatial attention by observing numbers would induce the SNARC-spatial attention effect, in the present study we have combined a parity judgment task with direct brain measurement of spatial attention.

In this study we combined the steady-state visual evoked potential (SSVEP) technique with a parity judgment task as an alternative approach to provide further evidence that numbers induce spatial attention allocation while performing a SNARC task. The SSVEP has been extensively used to study attention because the amplitude of the SSVEP correlates with the amount of attention required by the task (Andersen & Müller, 2010; Müller, Teder-Sälejärvi, & Hillyard, 1998). The SSVEP is a rhythmic neural response that tracks a flickering sensory stimulus (a.k.a. photic drive; Luck, 2005; Regan, 1989) and can be induced with a flickering stimulation in the range from 1 to 100 Hz (Herrmann, 2001).

On the other hand, the parity judgment task allows evaluating the effects of allocation of spatial attention associated with the implicit expectation of numbers in the task (Doherty et al., 2005; Posner, 1980; Posner et al., 1980).

Thus, the main goal of this study was to use the SSVEP method to measure whether numbers elicit an *automatic shift of spatial attention* during a SNARC task. To do so, we combined the parity task with the SSVEP where the numbers, but not their magnitude, were relevant for the task: implicit attention. Because we did not explicitly manipulate spatial attention in our task, we could evaluate whether the simple observation of numbers would reveal an attention-modulation effect for four different flicker frequencies (15 Hz, 20 Hz, 24 Hz and 17.14 Hz). We hypothesized that numbers will induce the SNARC-spatial attention effect even though their magnitude is not relevant for the task. Therefore, we predicted that EEG data would reveal a SNARC-spatial attention modulation effect on the SSVEP amplitude for the different flicker frequencies, with larger effects for conditions with small-odd or large-even numbers for the flicker frequencies (because these are the furthest apart congruent conditions from the set of numbers used in our task) placed to the left and right of the visual field, respectively.

METHODS

Participants

Thirty subjects participated in the experiment. During EEG pre-processing, the data from one subject was rejected due to excessive eye-blink and artifacts in more than 30% of the trials. The data from the other 29 participants (12 males, mean age 25.38, two left-handed) were included in the final analysis. All subjects had normal or corrected-to normal vision. The study was conducted in accordance with the Declaration of Helsinki, relevant laws, and institutional guidelines, and was approved by the local ethics committee at the Psychology Department at the University of Amsterdam.

Participants signed an informed consent document prior to the beginning of the experiment and they were paid for their participation. Subjects are the same who participated in the target detection task and they had a break of 15 min between experiments. The order of the experiments was counterbalanced between subjects.

Task

We designed our task to evaluate the attention-modulation of the SNARC effect on the SSVEP amplitude in a parity judgment task for congruent (small numbers: left button and large numbers: right button) and incongruent (small numbers: right button and large numbers: left button) conditions. Participants were seated at a distance of approximate 90 cm from and at the level eye of a 24'' BenQ monitor (1,920 x 1,080 pixels) with a refresh rate of 120 Hz. Stimulus presentation and behavioral response collection were controlled by custom-written scripts in Matlab (The Mathworks, Natick, MA) using the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997).

Participants were requested to direct their gaze to the fixation point in the center of the screen (approximately 0.39° of visual angle -v.a.-; note that all measurements are approximate because subjects were not restrained e.g., by a chin rest) during the entire task. Participants were informed that numbers (0.86° v.a.) would be displayed on top of the fixation point and that they should press the left-mouse button to odd numbers and the right-mouse button to even numbers. This response mapping was not counterbalanced across subjects or experimental blocks. Participants were requested to respond as quickly and accurately as possible after stimulus presentation and they did not receive feedback on their performance. Figure 4.2 shows the timeline of a trial sequence presented to each participant.

On each side of the fixation point (1° v.a. from fixation) two columns of flickering dots (0.11° v.a. wide each dot) were presented and participants were requested to ignore these flickering dots since they were not relevant for the task. The four columns flickered at a particular frequency: 15 Hz to the leftmost side of fixation and 20 Hz to the left side of the fixation point; and 24 Hz to the right of the fixation point and 17.14 Hz to the rightmost side of fixation. The columns were 1° v.a. apart from each other. And both the fixation point and the flickering columns were presented continuously throughout each block. Square-wave times series were created for each frequency (50% on per frequency).

In each block, numbers were presented for 300 ms followed by an inter-stimulus interval (ISI) of 1200 ms and the ISI was the same on all blocks. The stimuli numbers were 1,2,3,4,6,7,8 and 9 and they were separated in two groups in such a way that on each block two even and two odd numbers were presented, and the total amount of even and odd numbers displayed were equal on each block. Although the same number could be presented at most two consecutive times, each group of numbers was presented in pseudo-randomized order with the restriction that the same group of numbers was not presented consecutively. Then each participant completed nine blocks, each comprising 79 trials lasting approximately 2 minutes. Self-paced breaks were given between blocks and the full session lasted 20 minutes.

Finally, subjects were visually and verbally instructed and performed a practice block of 79 trials before starting the actual experimental session.

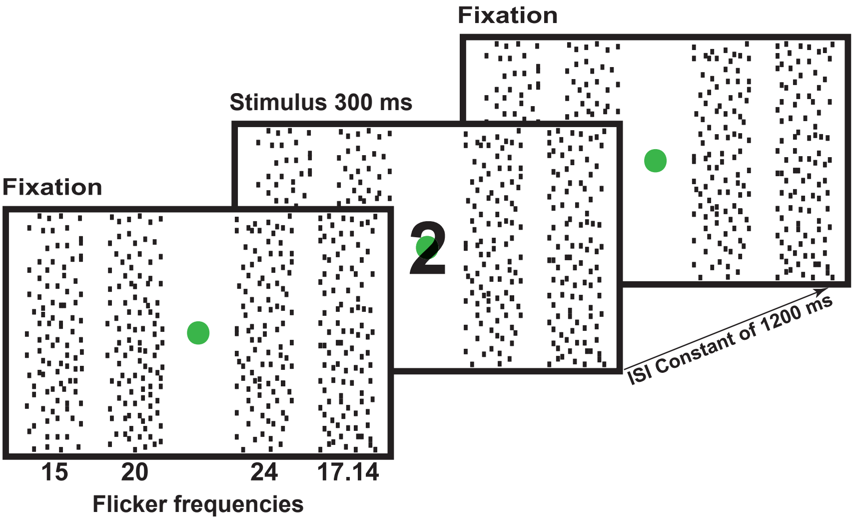


Figure 4.2. Example of the SNARC parity judgment task used in this study. Here an example of the individual time line presentation of one trial. The flicker frequencies in the *x* axis (15, 20, 24 and 17.14 Hz) correspond to the flicker rates in Hz for the corresponding columns. The presentation and the flicker rate for each column were constant throughout each block (see text for details).

Behavioral data analysis

Trials with RTs faster than 150 ms or slower than 2.5 standard deviations of the mean per condition and all error trials were excluded from behavioral analysis. From each participant, we computed number magnitude (small and large) and congruency (congruent for small odd numbers and large even numbers and incongruent for large odd numbers and small even numbers) obtaining four experimental conditions: small congruent (Scong), small incongruent (Sinc), large congruent (Lcong) and large incongruent (Linc). The statistical analyses of the four experimental conditions were performed using the statistical software SPSS 24.0 (SPSS, Chicago, IL).

The analyses for the differences between conditions were tested using repeated measures analyses of variance (ANOVA) with factors: number magnitude (for small: 1,2,3,4 and large: 6,7,8,9 numbers) and congruency (congruent and incongruent). Behavioral responses for accuracy were collected as correct or incorrect. Correct responses were defined as the response within the defined time window for RTs and the response button corresponding to the number displayed (left for odd and right for even numbers). Target presentation without response or responded with the incorrect button (left for even or right for odd numbers) were defined as incorrect response. However, because accuracy was defined as a binary response (right or wrong) only right responses were included for further analysis.

In cases of violation of sphericity, significance levels were adjusted using the Greenhouse-Geisser correction when performing repeated-measures ANOVA, and all the effect sizes are reported as partial eta-squared (η_p^2) or Cohen's *d*, when appropriate.

EEG recordings and preprocessing

The EEG data were recorded with a sampling rate of 1024 Hz from 64 scalp electrodes. Two additional electrodes were placed in the outer canthi of each eye to measure horizontal eye movements (HEOG). All data were collected using a BioSem Active Two system (see www.biosemi.com for details). Data were preprocessed with the EEGLAB toolbox for Matlab (Delorme & Makeig, 2004).

The data were high-pass filtered offline at 0.5 Hz and re-referenced off-line to the scalp average. After baseline subtraction (-200 to 0 ms pre-stimulus base line), trials with muscle and blinking artifacts during the stimulus were visually identified and manually removed (average of 6%). Then, additional artifacts or any kind of noise not related with brain activity were removed using independent component analysis in EEGLAB (Delorme & Makeig, 2004). All the EEG analyses involved only correct trials.

SSVEP analysis

We performed two sets of analyses on the SSVEP data for each of the flickering frequencies used in the experiment: “static SSVEP”, in which the fast-Fourier transform (FFT) was computed over the full time window of each trial (0 to 1500 ms), and “dynamic SSVEP”, in which a narrow band-pass Gaussian filter was applied to inspect the time-varying changes in SSVEP amplitude. Whereas the former method provides higher frequency resolution and increases the signal-to-noise (SNR) characteristics, the latter method provides higher temporal precision and thus the ability to detect time-varying changes in SSVEP amplitude resulting from phasic tasks events. The time windows for analysis were applied equally to all conditions.

SSVEP was extracted using a spatial filtering method termed rhythmic entrainment source separation (RESS; Cohen & Gulbinaite, 2017). The RESS method involves using generalized eigendecomposition to construct an optimal spatial filter that maximizes the SSVEP effect. The eigenvector with the largest eigenvalue maximally differentiates two covariance matrices (a “signal” and a “reference” covariance matrix), and that vector is used as channel weights to combine data from all electrodes. The signal covariance matrix was obtained from the narrowband-filtered signal at each stimulus frequency. The reference covariance matrix was obtained from data filtered at the closely spaced up- and down-neighbor frequencies. Importantly, the spatial filters were computed per frequency pooling data across all conditions; thus, although the spatial filter maximizes the overall SSVEP amplitude, there is no potential for biasing any condition comparison. The power spectrum was computed via the FFT for each flicker condition (15 Hz, 20 Hz, 24 Hz and 17.14 Hz), pooling over magnitude and congruency conditions over the entire trial time window. The static SSVEP was computed as the SNR as the ratio of the power at the flickered frequency to the average of neighboring frequencies surrounding each frequency (± 2 Hz, excluding a 0.5 Hz window around each center frequency) allowing us to convert power spectrum into SNR units to facilitate comparability across groups. See Figure 3.1 in chapter 3 as an example of the topographical maps and SNR spectra obtained with RESS spatial filter.

For the computation of the dynamic SSVEP amplitudes, a narrow-band Gaussian filter was implemented for each of the flicker conditions with a full width at half-maximum (FWHM) of 6 Hz (the standard deviation of the filter; while a narrow filter provides better spectral precision the temporal precision is reduced, therefore we use a high FWHM to increase the temporal resolution of the filter). This Gaussian was point-wise multiplied by the power spectrum of the EEG data, and the inverse Fourier transform was applied to reconstruct the time course of the activity (i.e., convolution). After filtering the data, the amplitude of the frequencies of interest was extracted as the square magnitude of the result of the Hilbert transform. We call this time series the “SSVEP amplitude time series”. To facilitate comparisons across subjects, the SSVEP time series were baseline-normalized to a pre-stimulus period of -600 to -200 ms, separately for each frequency and condition specific. Note that in our task the flickering stimulus was present all the time, including the peri-stimulus period, thus the baseline was computed using the average of all conditions within each frequency, allowing for detection of possible condition differences at peri- and post-stimulus activity. Baseline normalization allows rescaling the activity relative to the selected baseline, which facilitates comparison between frequencies (Cohen, 2014).

SSVEP statistical analysis

An initial visual inspection of the SSVEP results was performed for all the subjects and all the four flickering frequencies (15 Hz, 20 Hz, 24 Hz and 17.14 Hz) to confirm the SSVEP effects of the experimental paradigm. However, the statistical analyses were performed for the flickering stimuli closer to the fixation point (20 Hz and 24 Hz), first, because the analyses were focused on observing differences between the different experimental conditions and not between different flickering frequencies, and these two frequencies were optimal for further analysis; second, after performing initial analyses we didn’t observed significant effects for the 15 Hz and 17.14 Hz, and because these two frequencies were used as control conditions for the attention-modulation effects on the task. The SNR analyses for the differences between conditions were tested using repeated measures ANOVA with factors number magnitude (small and large), frequency (20 Hz and 24 Hz) and congruency (congruent and incongruent). In order to detect time-varying changes in SSVEP amplitude resulting from phasic task events, statistical analyses of the EEG SSVEP amplitudes time series were implemented for these eight experimental conditions (number magnitude, flicker and congruency). Nonparametric permutation testing was used in combination with cluster correction to evaluate condition differences in dynamic SSVEP over time (Maris & Oostenveld, 2007). To create a distribution of null-hypothesis time courses, the difference of the congruent – incongruent conditions for each frequency and number magnitude factor, for each subject was computed, and then multiplied this condition difference for a random subset of subjects by -1 (which is equivalent to randomizing incongruent – congruent vs. congruent – incongruent). This was repeated for 1,000 iterations. Finally, cluster correction was implemented to correct for multiple comparisons over the all-corresponding time points of the selected time window with a threshold value for pixel and cluster-levels of $p = .05$.

RESULTS

Behavioral results

Here we report only the relevant significant ANOVA results; see Table 4.1 for descriptive statistics and additional inferential statistics. For the RTs significant effects were observed for the number magnitude ($F(1,28) = 21.05$, $p < .001$, $\eta_p^2 = .429$), and congruency ($F(1,28) = 18.80$, $p < .001$, $\eta_p^2 = .402$) factors and the interaction between number magnitude and congruency ($F(1,28) = 13.36$, $p = .001$, $\eta_p^2 = .323$) meaning that participants were faster in the congruent conditions (M = 465.55 ms, SE = 10.59) as compared to the incongruent conditions (M = 485.31 ms, SE = 11.31) (Figure 4.3). Similarly, participants observed faster responses in trials presenting numbers with small magnitude (M = 468.98 ms, SE = 10.40) as compared when the stimulus was a large magnitude number (M = 481.87 ms, SE = 11.20) (Figure 4.3a).

For all the conditions, accuracy was above 90%. Congruent trials showed a significant effect as compared with incongruent trials (M = 97.4, SE = 0.5 and M = 94.8, SE = 0.6; $F(1,28) = 12.42$, $p = .001$, $\eta_p^2 = .307$) (Figure 4.3b), meaning that participants were more accurate classifying the stimulus number as odd or even when the response button was in the same side as the position of the number (e.g., small numbers with the left hand and large numbers with the right hand) as compared with trials where the response button was in the opposite side of the number and its mental representation (e.g., small numbers with the right hand and large numbers with the left hand). The results for the effects of number magnitude factor and the interaction between congruency and number magnitude were not significant. Because the response mapping was not counterbalanced across subjects or experimental blocks, we analyzed the individual performance regarding the hand response and number magnitude. With this we wanted to 1) confirm our group behavioral results and; 2) provide additional behavioral evidence for the presence of the SNARC effect regarding the not counterbalance response mapping. Repeated-measures ANOVA for subjects average with factors hand (left or right) and number magnitude (small or large) showed significant effects for the hand ($F(1,28) = 14.05$, $p = .001$, $\eta_p^2 = .335$) and number magnitude ($F(3,84) = 17.578$, $p < .000$, $\eta_p^2 = .386$) factors as well as for the response hand X magnitude interaction

($F(3,84) = 20.87$, $p < .000$, $\eta_p^2 = .427$). These results support the SNARC effect we observed in our task (Figure 4.4). Altogether, our behavioral results showed that we could replicate the SNARC effect in the parity judgment task as has been described in previous studies, supporting the target-stimulus related notion of the SNARC effect.

Table 4.1. Behavioral statistical results from all the conditions

		Reaction times (ms)		Accuracy (%)	
Number magnitude	**Congruency condition**	**Mean**	***SD***	**Mean**	***SD***
Descriptive statistics					
Small	Congruent	488.68	54.28	97.80	2.86
	Incongruent	489.28	64.15	94.89	3.32
Large	Congruent	482.41	64.32	97.01	3.14
	Incongruent	501.33	61.24	94.70	4.78

Variable	***df***	***F***	***p*****
Repeated measures ANOVA for reaction times			
Number magnitude	1	21.050	.000
Congruency	1	18.796	.000
Number magnitude X Congruency	1	13.359	.001
Repeated measures ANOVA for accuracy			
Number magnitude	1	1.141	.295
Congruency	1	12.417	.001
Number magnitude X Congruency	1	.346	.561

Note: Upper table contains the descriptive statistics for RTs and accuracy. Middle and bottom tables contain the ANOVA results for RTs and accuracy, respectively. *SS* = sum of squares; *MS* = mean square. *$p < .05$

EEG results

SNR results

We focused our EEG SSVEP analyses in the 20 Hz and 24 Hz flicker frequencies (see Methods). The SNR spectra exhibited robust peaks at both of these flicker frequencies, indicating that the design of our experiment was appropriate to elicit robust SSVEP effects during parity judgment task. The group average results showed RESS topographical maps with high SNR for the 20 Hz and 24 Hz. And high power spectrum at the corresponding frequencies was also observed in the group average for both experimental conditions: congruent (small number/left button, large numbers/right button) and incongruent (small numbers/right button, large numbers/left button) (Figure 4.5).

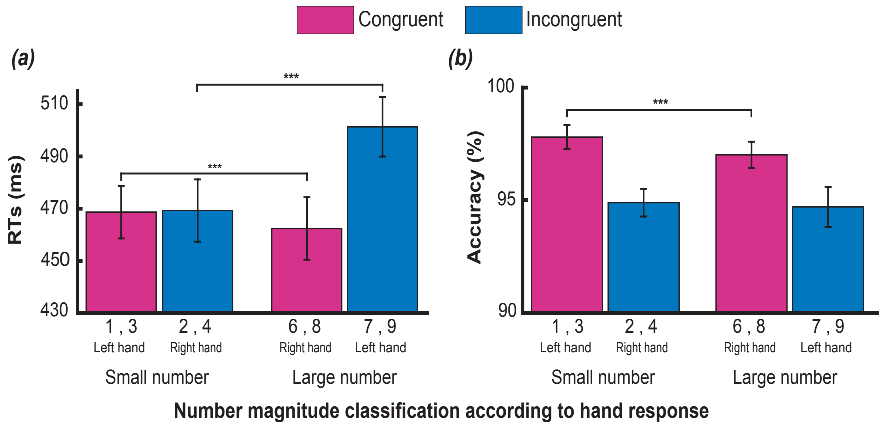


Figure 4.3. Behavioral responses parity judgment task (odd-left hand, even-right hand). a) RTs across subjects. Significant effects for the magnitude number (small/large) and congruency (congruent/incongruent) factors were observed. Participants showed faster response for congruent conditions as described by the SNARC effect. b) Accuracy was higher for congruent vs. incongruent trials. And better performance was observed for congruent trials with small numbers as compared with congruent trials presenting large numbers. Note that this improvement in performance was not statistically significant (number magnitude factor $p > .1$). Error bars represent standard error of the mean. *** $p < .001$

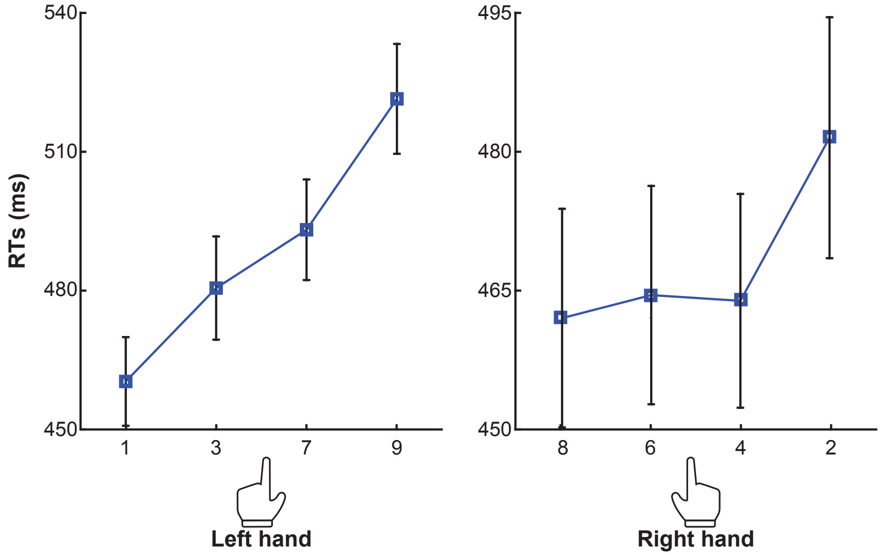


Figure 4.4. RTs obtained by number and response hand across subjects. The SNARC effect was observed for each number according to the button response: faster RTs with the left hand for 1 and 3 and for the right hand numbers 8 and 6. Error bars represent standard error of the mean.

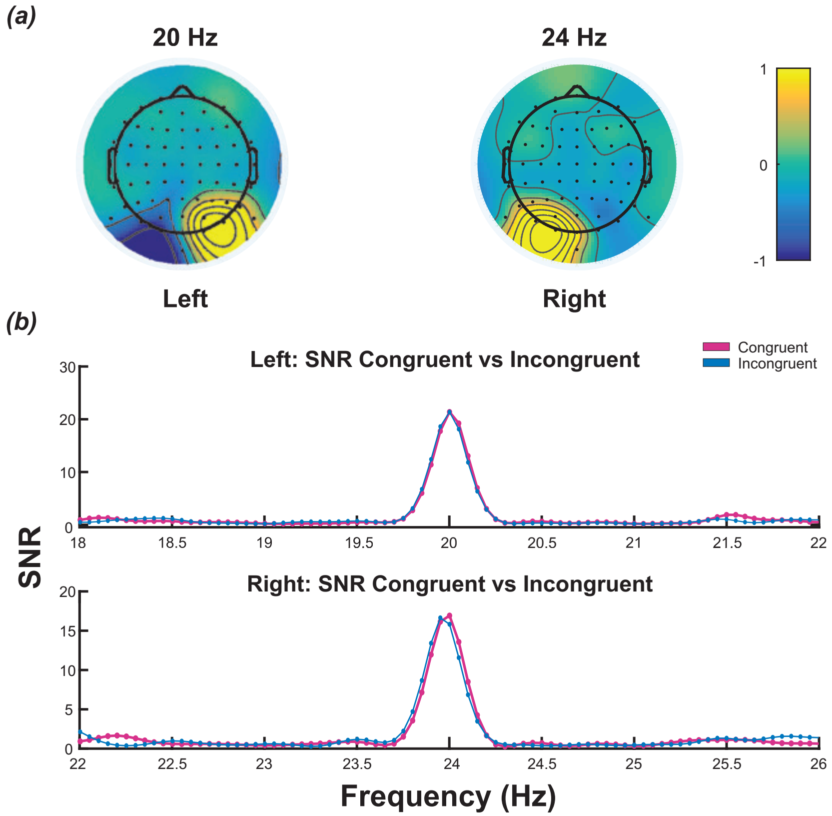


Figure 4.5. Group average SSVEP results. (a) Topographical maps across subjects for the flicker stimulus closest to the fixation point (20 Hz to the left, 24 Hz to the right). (b) Average SNRs per frequency (20 Hz top, 24 Hz bottom panel) for the congruent and incongruent conditions. Values in the *y* axis correspond to converting power spectrum to SNR units.

Our key hypothesis was that observation of numbers would produce the SNARC-spatial attention effect during the parity judgment task, therefore we expected SSVEP SNRs to be higher in 20 Hz (placed to the left of fixation) for small magnitude numbers and 24 Hz (placed to the right of fixation) for large magnitude numbers in the congruent conditions.

Repeated-measures ANOVA (with factors number magnitude, congruency and frequency) showed significant main effects for the frequency factor ($F(1,28) = 18.87$, $p < .001$, $\eta_p^2 = .403$). However, neither the main effect for congruency ($F(1,28) = .002$, $p > .965$, $\eta_p^2 = .000$), the number magnitude ($F(1,28) = 2.98$, $p > .095$, $\eta_p^2 = .096$) nor any of the interactions involving magnitude number, all *p's* > .1 were significant. Figure 4.6 shows bar plots of the SNR for the 20 Hz and 24 Hz flicker frequencies for both congruent and incongruent conditions.

Higher SNRs can be observed for the flicker placed to the left of fixation (20 Hz) for both the congruent and incongruent condition with small (a) and large numbers (b) as compared with the flicker placed to the right of fixation (24 Hz). Also, in the upper panel it can be observed that for the flicker on the right the SNR was higher for the congruent conditions when displaying small numbers (i.e., numbers 1 and 3) as compared with incongruent trials (i.e., numbers 2 and 4), this large difference between the congruent and incongruent conditions was not observed for the flicker on the left. On the other hand, in the lower panel it can be observed that for the right flicker the SNR for congruent conditions with large numbers (i.e., 6 and 8) showed smaller SNR as compared with the incongruent conditions with large numbers (i.e., 7 and 9).

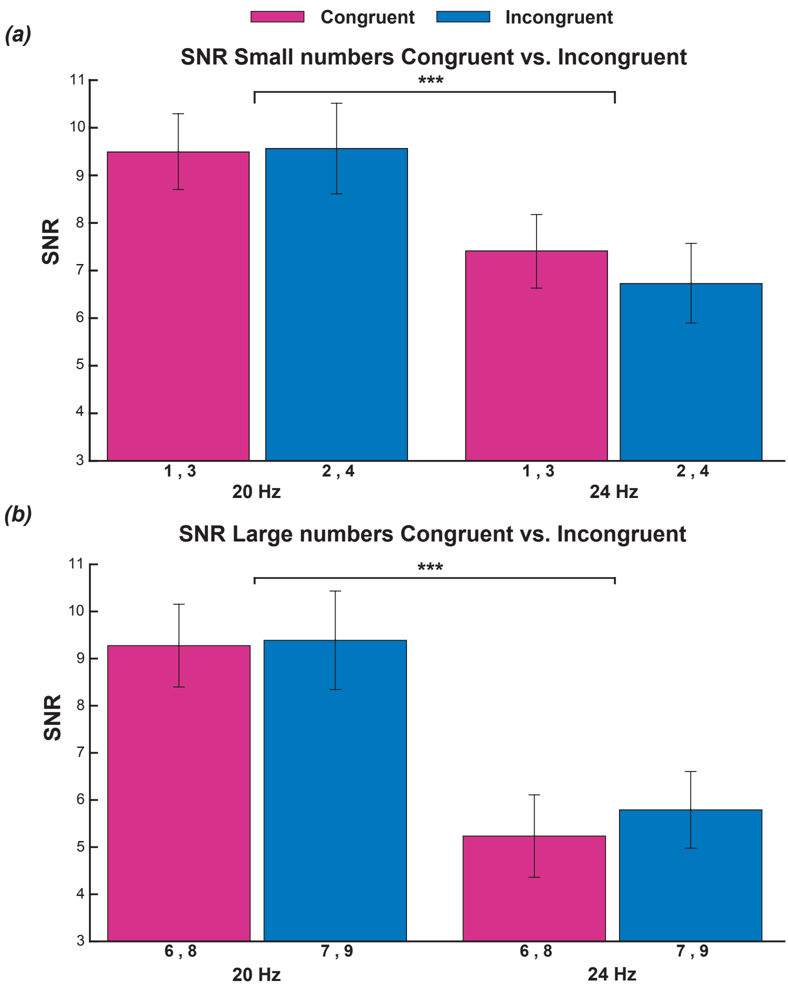


Figure 4.6. Statistical main effects were obtained for the frequency factor for the SSVEP SNR. Note that SNR values were higher for the flicker frequency placed to the left of the fixation point (20 Hz) as compared with the flicker stimuli to the right (24 Hz) for trials with (a) small or (b) large magnitude numbers (See figure 4.2). Values in the *y* axis correspond to converting power spectrum to SNR units. Error bars represent standard error of the mean. *** $p < .001$

Although we did not obtained any statistically significant effects involving the magnitude factor, we performed a post hoc analysis in which we compared the SNRs between small vs. large numbers where we computed the average of the small numbers for the left (20 Hz) and right (24 Hz) flicker compared to the average of the large numbers. Paired samples *t* test showed no significant effects between small and large numbers (all *p's* > .1). Table 4.2 contains all the ANOVA and *t* test results for the left (20 Hz) and right (24 Hz) flicker SNRs.

Table 4.2. SNR Repeated measures ANOVA

Variable	*df*	*F*	*p**	ε **
Repeated measures ANOVA for SNR				
Number magnitude	1	2.978	.095	.096
Congruency	1	.002	.965	.000
Frequency	1	18.869	.000	.403
Number magnitude X Congruency	1	.497	.487	.017
Number magnitude X Frequency	1	1.372	.251	.047
Congruency X Frequency	1	.028	.867	.001
Number Magnitude X Congruency X Frequency	1	.429	.518	.015

Pair	**Mean**	**SD**	**95% CI of the difference**		***r***	***t***	***df***	**Sig. (2-tailed)**
Results of the *t* test and descriptive post hoc statistic for SNRs								
Small numbers	.6305	4.82	-1.2019	2.4630	-.03	.70*	28	.487
Large numbers								

Note: *SS* = sum of squares; *MS* = mean square. *p < .05. ** ε = *Epsilon Greenhouse-Geisser correction*.

Dynamic SSVEP results

The static SSVEP exhibited high SNR, but it is possible that the *automatic shift of spatial attention* was transient, and therefore it might not have been visible in the static analysis, which requires a long time window for spectral resolution. Therefore, we applied a dynamic SSVEP amplitude analysis to search for temporally localized modulations. Our key hypothesis was that observation of numbers would produce the SNARC-spatial attention effect during the parity judgment task, therefore, we expected SSVEP amplitudes to be higher for the flicker on the left (20 Hz) and on the right (24 Hz) for the small and large magnitude numbers, respectively.

To facilitate comparison between frequencies we performed the percentage change baseline normalization to a pretrial baseline of -600 to -200 ms (See Methods). Because the flicker stimulation was continuous over time, meaning that any change relative to baseline is relevant, we first evaluated whether each flicker condition deviated from 100% (i.e., baseline). Therefore we performed a t-test for the difference between every time point from each of the flicker condition against 100 (all p values < .05, cluster-corrected for multiple correlated tests over time points, see Methods and Figure 4.7).

Thus, initially we pooled all the conditions by congruency and flicker factors to identify any changes in the SSVEP amplitude of the flicker frequencies. For the left and right visual field flicker we observed statistically significant changes above the baseline for the congruent and incongruent conditions. Regarding the left flicker congruent conditions a significant increasing in SSVEP amplitude was observed during the time of stimulus presentation and reaching its higher peak at 432 ms after stimulus onset and decreasing again until reaching the 100% (i.e. baseline). And from 658 ms to the end of the data epoch the SSVEP amplitude showed a significant increasing again. Additionally, for the left flicker congruent conditions two different time windows showed significant changes with respect to the baseline. The first time window was between 250 and 530 ms and the second time window was between 1017 ms to the end of the data epoch (Figure 4.7a). For the left flicker incongruent conditions a significant increasing in SSVEP amplitude was observed from before the stimulus onset and gradually decreasing until reach the 100% at 682 ms. Then, two more significant changes were obtained one between 837 and 1010 ms and the second one from 1125 ms to the end of the data epoch. For the incongruent conditions the statistically significant time window difference between the SSVEP amplitude with respect to the baseline was observed between 1285 and 1375 ms (Figure 4.7b).

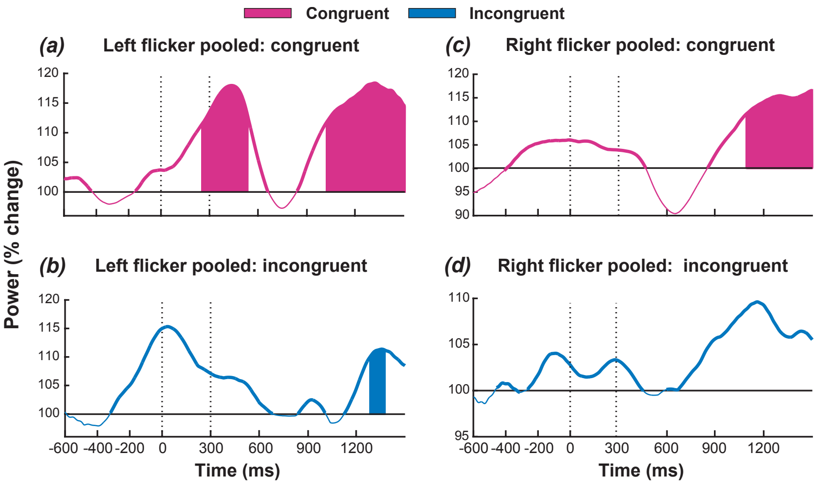


Figure 4.7. SSVEP changes in amplitude for the left (a, b) and right flicker (c, d) stimuli pooled over number magnitude for (a, c) congruent and (b, d) incongruent conditions. Thicker lines represent when changes are above zero from baseline and thinner line represent changes below baseline. *y* axis corresponds to SSVEP percentage change amplitudes. Shaded areas represent statistically significant temporal differences between the observed increasing in the SSVEP and the baseline (i.e., 100%). Dotted line at time 0 represents time stimulus onset and dotted line at 300 ms represents the stimulus offset. $p <$ .05

For the right flicker congruent conditions significant SSVEP amplitude changes with respect to the baseline were observed before stimulus onset from -391 ms to 465 ms, and from 852 ms to the end of the data epoch. The statistically significant time window difference between the SSVEP changes with respect to the baseline was observed between 1092 ms to the end of the data epoch (Figure 4.7c). For the right flicker incongruent conditions significant changes in the SSVEP amplitude were obtained from -274 ms before stimulus onset to 451 ms and after stimulus offset and from 583 ms to the end of the data epoch. For the right flicker incongruent conditions there were no statistically significant time windows differences between the baseline and the SSVEP changes in amplitude (Figure 4.7d).

The observed significant changes in the SSVEP amplitude for both flicker frequencies reflect the attention modulation effects resulting from observation of numbers while participants classified them as odd or even. Note however that significant changes in the SSVEP amplitude observed before stimulus onset correspond to the time period used for baseline normalization.

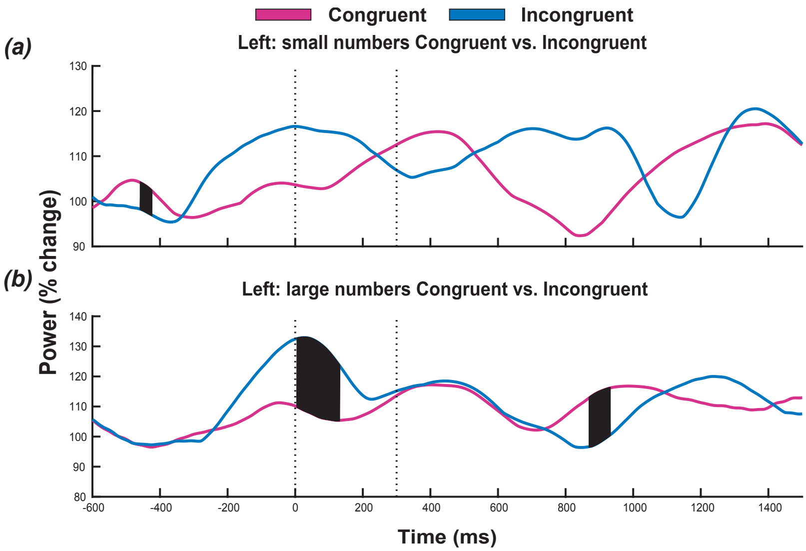


Figure 4.8. Dynamic SSVEP for the flicker frequency to the left (20 Hz) for small (a) and large magnitude numbers (b). Pre stimulus time between -600 to -200 ms corresponds to the baseline-normalization period. *y* axis correspond to SSVEP percentage change amplitudes. Dotted line at time 0 represents time stimulus onset and dotted line at 300 ms represents the time stimulus offset. Shaded areas represent statistically significant differences between conditions. Notice that the shaded area representing statistically significant differences (from -462 to -417 ms) corresponds to the time window in the baseline period used for normalization. $p < .05$

Then, we proceeded to evaluate the dynamic SSVEP for each of the congruent and incongruent conditions, separately for the left and right flicker (all *p* values <

.05, cluster-corrected for multiple correlated tests over time points). For the left flicker when small numbers (1,2,3,4) where displayed we did not obtain any statistically significant differences in the SSVEP amplitude between the congruent and incongruent conditions after the stimulus presentation (Figure 4.8a).

On the contrary, when large numbers were displayed (6,7,8,9) significant effects were observed at two different time windows (Figure 4.8b) between the congruent and incongruent conditions. First, increasing SSVEP amplitude for the time window between 0 and 125 ms was observed for the incongruent conditions, but after stimulus presentation the increasing in the SSVEP amplitude was observed for the congruent conditions in the time interval between 868 and 931 ms. Figure 4.9b shows the results of the nonparametric permutation testing that was used in combination with cluster correction to evaluate condition differences in the dynamic SSVEP over time for correct trials and the left flicker frequency.

For the flicker stimuli on the right, statistically significant effects in the SSVEP amplitude were observed for congruent trials in the time window between 1225 ms and 1284 ms after stimulus offset as compared with incongruent trials when small numbers stimuli were presented (Figure 4.9a). Regarding trials displaying large numbers no significant effects in the change of the SSVEP amplitude were observed between the congruent and incongruent conditions (Figure 4.9b). Figure 4.9 shows the results of the nonparametric permutation testing that were used in combination with cluster correction to evaluate condition differences in dynamic SSVEP over time for correct trials for the right flicker.

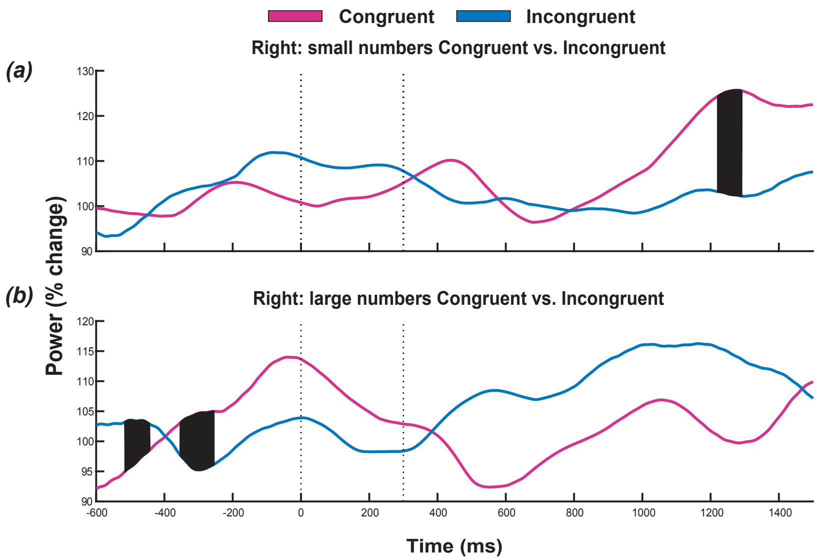


Figure 4.9. Results for the flicker frequency to the right (24 Hz) for the small (a) and large magnitude numbers (b). Arrangement of Figure 4.9 is the same as in Figure 4.8. Notice that the shaded areas representing statistically significant differences (in the time windows between -513 and -49 and -345 to -254 ms) correspond to the time window in the baseline period used for normalization. $p < .05$

DISCUSSION

In this study we have used the parity judgment task to induce the so-called SNARC effect and to evaluate whether the simple observation of numbers, when their magnitude is irrelevant, has an attention-modulation effect in the SSVEP amplitude producing the so-called SNARC-spatial attention effect. We implemented a parity judgment task because it is the most frequently task used to study the SNARC effect (Wood, Willmes, Nuerk, & Fischer, 2008), allowing the evaluation of possible implicit spatial attention elicited by seeing the numbers. In our design, participants classified a number as odd or even with the hand response mapping left for odd and right hand for even numbers. We observed significant changes in the SSVEP amplitude with respect to the baseline for the left (20 Hz) and right (24 Hz) flicker for both, the congruent and incongruent conditions. And statistically significant differences between the congruent and incongruent conditions were larger for the congruent conditions for the flicker stimuli on the left. Our results support the interaction between numbers and space as described by the SNARC effect (Dehaene et al., 1993; Fias & Fischer, 2004a) and provide psychophysiological evidence for the hypothesis that observing numbers, even if their magnitude is irrelevant (i.e., parity task), has an effect in the automatic allocation of spatial attention, the so-called SNARC-spatial attention effect.

Our study is the first approach to evaluate the SNARC effect using the SSVEP in a parity judgment task. Behaviorally we have shown that indeed our task induced the SNARC effect improving performance for the congruent versus the incongruent conditions. Our results are in line with previous studies (Chinello et al., 2012; Göbel et al., 2006; Schwarz & Keus, 2004) confirming the positive effect between mental representation of space and numbers while performing a task that involves numbers, even if their magnitude is not relevant for the task (i.e., the parity task). We observed a positive interaction between numbers magnitude and hand response in reaction time and proportion of correct responses, meaning that for small odd numbers the response time and accuracy performance was better when responded with the left hand as compared with large odd numbers and left hand. And similar performance was observed for large even numbers when responded with the right hand as compared with small even numbers. These results are also consistent with the hypotheses that the way numbers are mentally represented have an effect on performance when there is a relation between the magnitude of the number and the spatial response. And we interpret our results as supporting evidence for the interaction between numbers and space as explained by the MNL and also by the SRC model, but not exclusively one or the other, which is consistent with Santens & Gevers (2008) who claimed that the SNARC effect does not necessarily reflect the mapping between number magnitude and response positions, but that there is an intermediate stage where stimuli are categorized producing a preferential mapping that relies on linguistic features. It is beyond the scope of this report to include comprehensive assessments of the various SNARC effect theories, but readers are directed to (Fias & Fischer, 2004b) and (Bonato et al., 2012) for an extended review of the SNARC effect.

SSVEP results and the SNARC effect.

In this study we evaluated whether numbers have an effect allocating spatial attention during a non-spatial attention task and we included the SSVEP in our paradigm to elucidate if that could be the case in the parity judgment task. Because it has been shown that SSVEP amplitude increases as a function of attention (e.g., Andersen & Müller, 2010; Ding, Sperling, & Srinivasan, 2006; Müller et al., 1998) even if the flicker is irrelevant for the task (Hillyard et al., 1997), we expected changes in the SSVEP amplitude to be larger for congruent as compared with the incongruent conditions. Our results provided evidence supporting the hypothesis that observation of numbers – even without actively processing their magnitude – induced the SNARC-spatial attention effect during the parity judgment task. We observed contralateral SSVEP topographical responses for each of the flickering stimuli at posterior sites (Figure 4.5) that are consistent with the observed hemifield response in a regular visuospatial attention paradigm (Corbetta & Shulman, 2002; Hopfinger, Buonocore, & Mangun, 2000). And the SSVEP responses for congruent conditions showed significant changes in the amplitude as compared with incongruent conditions after stimulus offset (Figures 4.8 and 4.9). These results support the hypothesis that number observation induces allocation of spatial attention, meaning that numbers boost SSVEP amplitude being larger for the hemifield cued by number magnitude. The observed changes in the SSVEP amplitude are consistent with the attention effects previously described in spatial attention (Morgan, Hansen, & Hillyard, 1996; Müller, Malinowski, Gruber, & Hillyard, 2003); and, since in our task participants were requested to ignore the flickering stimulus, the observed effects can be attributed to the allocation of attention to one specific visual hemifield when the observed number is spatially related to the attended hemifield (Fischer et al., 2003) and its position in the MNL theory (Dehaene et al., 1993).

It has been proposed that the SNARC effect is evidence for the automatic activation of number magnitude even when the magnitude is irrelevant for the task (Dehaene et al., 1993; Schwarz & Heinze, 1998) as in the parity task. To further evaluate the effect between large and small numbers in the allocation of spatial attention, we evaluated the difference between congruent and incongruent conditions for the small and large numbers separately for each flicker frequency. For the SSVEP response in the left hemifield, trials displaying large magnitude numbers showed significant increasing of the SSVEP amplitude for congruent trials as compared with incongruent trials and no significant differences were observed for the left flicker when small numbers were display. Similarly, the SSVEP response in the right hemifield showed a significant effect for the congruent conditions when small magnitude numbers were displayed. These results confirm that, although number's magnitude was not relevant for the task it is possible that numeric semantic information was activated (Sandrini & Rusconi, 2009), which in turn may have induced a shift in spatial allocation of attention. This is consistent with the contralateral hemispheric activation in visual tasks as previously described

(Ranzini et al., 2009; Salillas, El Yagoubi, & Semenza, 2008). Our results provide physiological evidence for the hypothesis that observing numbers has an effect on spatial attention, driving covert spatial attention toward the position of number's magnitude in the MNL while making a decision possibly because during the classification of the number as odd or even its number semantic is activated.

SNARC effect and hand mapping response.

Our study is the first approach, to our knowledge, to evaluate the SNARC effect using the SSVEP and it could be argued that using only one response mapping we didn't control for the effects of the responding hand. However, previous studies have shown that the SNARC effect is determined by the spatial position of the response (e.g., number magnitude) and not by the responding hand when using crossed-over hands (left hand pressing right button; Dehaene et al., 1993, Experiment 6), or during unimanual tasks (Fischer, 2003). Similarly, Dehaene et al. (1993) reported the presence of the SNARC effect for left-handed participants (Experiment 5) and during crossed hands experimental conditions on the response button (Experiment 6). Then, our behavioral results and the individual analysis of performance between hand response and number stimulus are consistent with previous studies and support the validity of our experimental design regarding the non-counterbalancing of hand mapping (Gut et al., 2012). Nonetheless, we strongly recommend counterbalancing the hand response mapping in future SNARC-SSVEP studies in order to elucidate the possible effects of different response mappings.

CONCLUSION

This study has provided behavioral and EEG evidence for the effects of the mental representation of numbers, the mental representation of space, and the interaction between them during a parity task improving performance. On the other hand, we have also provided some relevant evidence for the use of the SSVEP technique to study and better understand the SNARC effect, mental representation of numbers, and how these two processes interact to have an effect on cognition while observing numbers. Our results are in line with different cognitive models explaining the SNARC effect (e.g., MNL, the SRC, dual-route or the PCT models) and support the hypothesis that when numbers are part of the task but their magnitude is not task-relevant, number semantics are activated having an effect on allocating spatial attention, the so-called SNARC-spatial attention effect. Therefore, the SNARC-spatial attention effect as shown here is present when numbers are relevant for the task. The EEG SSVEP evidence we obtained supports the thesis that the SNARC effect is a cognitive effect resulting from the mental representation of numbers and its relation with the space representation, more than merely a motor effect. Nonetheless, in order to further confirm our results and/or provide stronger evidence of the SNARC effect in the SSVEP amplitude results during a parity judgment task, some modifications of the paradigm and the task are recommended.

ACKNOWLEDGEMENTS

A. M. C. is funded by Departamento Administrativo de Ciencia, Tecnología e Innovación, Colciencias call 529/ 2011 (Colombia). M. X. C. is funded by an ERC-StG 638589. R.G. is funded by an ERC awarded to Dr. Rufin Vanrullen (CerCo institute, Tolouse, France).

DECLARATION OF INTEREST STATEMENT

The authors declare that there are no conflicts of interests.

AUTHOR CONTRIBUTIONS

M.X.C. and R.G. conception and design of research; M.X.C. analysed data; A.M.C. performed experiments; analysed data; M.X.C. and A.M.C. interpreted results of experiments; A.M.C. prepared figures; drafted manuscript; A.M.C., M.X.C. and R.K.R. edited and revised manuscript; M.X.C. and R.K.R. approved final version of manuscript.

Chapter 5

The role of task-irrelevant numbers in allocating spatial attention: The SSVEP and the spatial attention in a target detection task

ABSTRACT

In our previous experiment we obtained physiological evidence for the hypothesis that when numbers are part of the task but their magnitude is not relevant, mental number representations are activated; these numbers trigger the allocation of spatial attention, which induces the so-called SNARC-spatial attention effect. In this follow-up study we wanted to evaluate whether passively observing numbers induced an automatic shift of spatial attention, the SNARC-spatial attention effect. To do so, we implemented a modified version of Fischer's target detection task combined with the steady-state visual evoked potential (SSVEP). In our covert spatial attention task numbers preceded the presentation of peripheral targets while different nonrelevant flicker stimuli were constantly displayed on each side of the fixation point, two to the left visual hemifield (15 and 20 Hz) and two to the right visual hemifield (24 and 17.14 Hz). Behavioral results showed benefits for the interaction between large magnitude numbers preceding targets presented in the right hemifield, providing a partial replication of the SNARC behavioral effect. Additionally, our EEG SSVEP results showed an attention modulation effect for the difference between congruent – incongruent conditions, showing larger SSVEP amplitude for incongruent conditions (small numbers/targets on the right) for the flicker stimuli on the left hemifield and for the congruent conditions (large numbers/target on the right) for the flicker stimuli on the right. This means that for both flicker conditions, when the target was presented on the right hemifield, attention was already oriented towards the right space, independently of the magnitude of the number preceding it. These results demonstrate that passively observing numbers does not induce an automatic shift of spatial attention, or at least not an effect that could be measured electrophysiologically. They also demonstrate that even when numbers are irrelevant for the task, number semantic representation is activated. Overall, this study contributes to further understand the interaction between number magnitude, mental representation of space and the physiology of the SNARC effect.

Keywords: SNARC-spatial attention, target detection, SSVEP

Based on: *Mora-Cortes, A., Gulbinaite, R., Ridderinkhof, K.R., Cohen, MX. Numbers, the where of spatial attention and the SSVEP. Manuscript under preparation.*

INTRODUCTION

Our brain is constantly exposed to many stimuli and frequently the context requires us to selectively attend to a particular stimulus while ignoring other stimuli. The ability to direct attention in the visual field to a particular stimulus while suppressing the processing of any other competing stimuli is called spatial attention. Although this orienting of spatial attention is a voluntary activity, it has been proposed that numbers may have a particular effect on spatial attention (Fischer et al., 2003)

In the seminal study of Dehaene, Bossini, & Giraux (1993), authors reported the close relation between mental representation of numbers and spatial cognition, describing the association between number magnitude and response side where small numbers were associated with the left side and large numbers with the right side. They termed this as the Spatial-Numerical Association of Response Codes (SNARC) effect. Several follow-up studies have reported that during the SNARC effect the spatial processing of numbers is fast and automatic (Mapelli, Rusconi, & Umiltà, 2003), implying an automatic activation of spatial information (Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006) and that the SNARC effect is present even when numbers are not relevant during an attentional task (Calabria & Rossetti, 2005; Fias et al., 2001), possibly inducing a spatial bias in performance (Fischer, 2001).

Nonetheless, it was Fischer et al. (2003) who initially suggested the influence of number processing on allocation of spatial attention. In a covert spatial attention task authors asked participants to fixate at the center of the screen while detecting a target displayed either to the left or the right side of the fixation point. On each trial on top of the fixation point and before target presentation one out of four digits were displayed and participants were informed that the numbers were not relevant for the task. Authors concluded 1) that simply by observing numbers, an automatic shift of covert spatial attention was induced to the corresponding visual field; 2) this effect in spatial attention was not limited to motor responses but also was involved perceptual encoding processes; and 3) the attentional shifts between internal and external representation of space must underlie similar structures explaining this number-spatial-attention effect (see Fischer et al., 2003 for details).

However, this was a behavioral study and the results were based on reaction times (RTs) of a unimanual task. Since then, several studies have tried to replicate this observation, providing an important set of different results, thus questioning the assumption that numbers induce an *automatic shift of spatial attention*. On the one hand, Bulf, Cassia, & de Hevia (2014) reported a SNARC-spatial attention effect during a target detection task measuring participant’s saccade responses, and Dodd, Van der Stigchel, Leghari, Fung, & Kingstone (2008) reported the SNARC-spatial attention effect at 500 ms delay (out of two: 500 and 750 ms) as reported by Fischer. Other studies have replicated this SNARC-spatial attention effect, but suggested that these effects may be driven by different strategies rather than being due to the an automatic effect induced by numbers processing (Galfano et al., 2006; Ristic et al., 2006). And some further authors have failed to replicate this

SNARC-spatial attention effect altogether (Bonato, Priftis, Marenzi, & Zorzi, 2009; Casarotti et al., 2007; Fattorini, Pinto, Rotondaro, & Doricchi, 2015; Jarick, Dixon, Maxwell, Nicholls, & Smilek, 2009; Ranzini et al., 2009).

In line with these results, heterogeneous reports regarding the neural correlates of the SNARC effect and its possible effect on allocating attention have been described. While Cattaneo, Silvanto, Battelli, & Pascual-leone (2009), using transcranial magnetic stimulation (TMS) reported that number presentation in a mental number line fashion exerts an effect on covert spatial attention, inducing specific changes in the visual cortex, Goffaux, Martin, Dormal, Goebel, & Schiltz (2012) in an fMRI study reported that, additional to the failure to observe of the SNARC-spatial attention effect, numeral digits used as cues did activate occipital areas, but did not incur lateralized activations as involved in shifts of spatial attention (i.e., leftward activating right hemisphere and rightward activating left hemisphere).

Thus, the conclusion that merely observing numbers induces and *automatic shift of spatial attention* as the main reason for participants to observe better performance for the left side for small numbers and right-side for high numbers is not easy to confirm. And importantly, there is no direct brain evidence for a spatial shift of attention induced by the SNARC effect.

Providing physiological evidence of the *SNARC-spatial attention effect* seems relevant to better understand the role of numbers' magnitude in spatial processing (if so) and also to better understand how numbers are represented in the brain. In the previous chapter we obtained physiological evidence that during a parity task (classify numbers as odd or even), number magnitude is activated although it was not relevant for the task inducing the so-called *SNARC-spatial attention effect*. Similar to our previous study, here we used the steady-state visual evoked potential (SSVEP) and combined it with the target detection task as in Fischer et al. (2003). We used the SSVEP because it has been reported that during spatial attention tasks, covert attention shifts evidenced changes in amplitude of the SSVEP at posterior and contralateral sites for target detection compared to non-attended flickering stimuli (Belmonte, 1998).

Here we implemented a modified version of Fischer's target detection task where we explicitly manipulated covert spatial attention combined with the SSVEP to provide direct evidence (or lack thereof) for the hypothesis that simple observation of numbers would induce an *automatic shift of spatial attention* producing the so-*called SNARC-spatial attention effect*. If so, we would expect the amplitude of the SSVEP flicker frequencies (15 Hz, 20 Hz, 24 Hz and 17.14 Hz) to be higher relative to baseline. Specifically, we expected to observe higher SSVEP amplitudes and higher signal-to-noise (SNR) for the congruent conditions (target on the left preceded by small numbers and targets on the right preceded by large numbers) as compared to the incongruent conditions (targets on the left preceded by large numbers and targets on the right preceded by small numbers)

METHODS

Some of the procedures described in this chapter are the same as in chapter 4 and are repeated here for completeness.

Participants

Thirty subjects participated in the experiment. Data of four subjects were rejected due to poor behavioral performance. During the EEG pre-processing, the data from three subjects were rejected due to excessive eye-blink and artifacts in more than 30% of the trials and excessive lateral eye movements (i.e., left-right) at the time of target presentation. The data from the other 23 participants (9 males, mean age 25.6, two left-handed) were included in the final analysis. All subjects had normal or corrected-to normal vision. The study was conducted in accordance with the Declaration of Helsinki, relevant laws, and institutional guidelines, and was approved by the local ethics committee at the Psychology Department at the University of Amsterdam. Participants signed an informed consent document prior to the beginning of the experiment and they were paid for their participation. All the subjects participated in the previous SNARC parity judgment task. Subjects had a break of 15 min between experiments, and the experiments were counterbalanced between subjects.

Task

The target detection task was design to evaluate the covert shifts of spatial attention (if any) induce by numbers' magnitude according to the SNARC effect. Thus, a modified version of Fischer's task was implemented (Fischer et al., 2003). Participants were seated at a distance of approximate 90 cm from and at the level eye of a 24'' BenQ monitor (1,920 x 1,080 pixels) with a refresh rate of 120 Hz. Stimulus presentation and behavioral response collection were controlled by custom-written scripts in Matlab (The Mathworks, Natick, MA) using the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997).

Participants were requested to direct their gaze to the fixation point (approximately 0.39° of visual angle -v.a.-; note that all measurements are approximate because subjects were not restrained by e.g., a chin rest) in the center of the screen during the entire task. To each side of the fixation point (1° v.a. from fixation) two columns of flickering dots (0.11° v.a. wide each dot) were presented all time. And on top of the fixation point single numbers (0.86° v.a.) were displayed. Participants were requested to ignore both the flickering dots and the numbers presented since they were not relevant for the task. To each side of the fixation point and between the flickering columns there was a small box (5° v.a. from the fixation point and 1° v.a. wide) and participant should respond when the box was filled black (target) pressing the left or right-mouse buttons according to the position where the target was displayed (Figure 5.1).

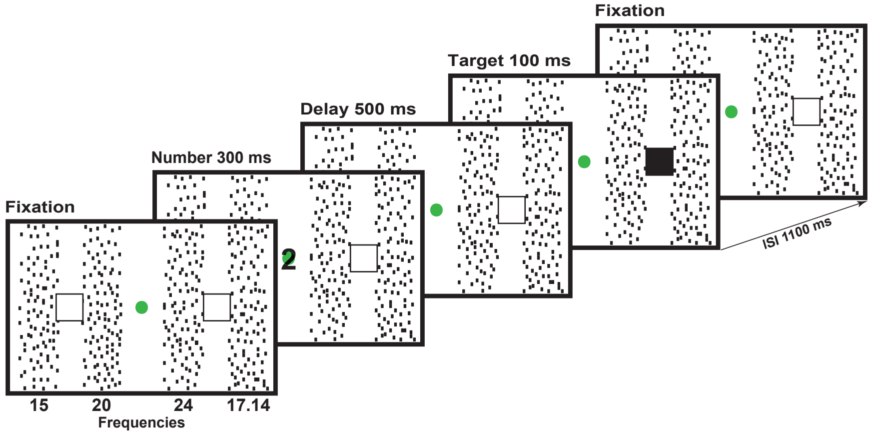


Figure 5.1. Display sequence of the SNARC-target detection task. Here the individual time line presentation of one trial. The flicker frequencies in the *x* axis (15, 20, 24 and 17.14 Hz) correspond to the flicker rates in Hz for the corresponding columns. The presentation and the flicker rate for each column were constant throughout each block (see text for details).

The four columns were flickering at a particular frequency: 15 Hz to the leftmost side of fixation and 20 Hz to the left side of the fixation point; and 24 Hz to the right of the fixation point and 17.14 Hz to the rightmost side of fixation. The columns were 1° v.a. apart from each other. Square-wave times series were created for each frequency (50% on per frequency). And both the fixation point and the columns were presented continuously along the whole block. On each block numbers were presented for 300 ms followed for a delay of 500 ms, then the target was presented for 100 ms and 1100 ms inter-stimulus interval followed the target presentation, these time parameters were the same on all blocks. The stimuli numbers were 1,2,3,4,6,7,8 and 9 and they were separated in two groups in such a way that on each block two even and two odd numbers were presented and the total amount of even and odd numbers were equal on each block. Although the same number could be presented at most two consecutive times, each group of numbers were presented in pseudo-randomized order with the restriction that the same groups of numbers were not presented consecutively. The percentage of target presentation (80 %) on each block, the time of number presentation and the delay before target presentation were similar to Fischer's task. Then each participant completed eight blocks, each comprising 59 trials and lasting approximately 2 minutes. Self-paced breaks were given between blocks and the full session lasted 20 minutes. The SNARC target detection task was performed on the same day and around 15 minutes after finishing the parity judgment task.

Finally, subjects were visually and verbally instructed and performed a practice block of 59 trials before starting the actual experimental session.

Behavioral data analysis

Trials with RTs faster than 150 ms or slower than 2.5 standard deviations of the mean per condition and all error trials were excluded from behavioral analysis.

From each participant, we computed the number magnitude (small and large) and target side presentation (left and right) obtaining four experimental conditions: small left (SmallL), small right (SmallR), large right (LargeR) and large left (LargeL). The statistical analyses of the four experimental conditions were performed using the statistical software SPSS 24.0 (SPSS, Chicago, IL). The analyses for the differences between conditions were tested using repeated measures analyses of variance (ANOVA) with factors: number magnitude (for small: 1,2,3,4 and large: 6,7,8,9 numbers) and congruency: congruent conditions (target on the left preceded by small numbers and targets on the right preceded by large numbers) and incongruent conditions (targets on the left preceded by large numbers and targets on the right preceded by small numbers). Behavioral responses for accuracy were collected as correct or incorrect responses. Correct responses were defined as the response within the defined time window for RTs and the response button corresponding to the position of the target presentation (left button for targets displayed on the left and right button for targets displayed on the right). Target presentation without response or responded with the incorrect button (right button for targets displayed on the left and left button for targets displayed on the right) were defined as incorrect response. However, because accuracy was defined as a binary response (right or wrong) only right responses were included for further analysis.

In case of violation of sphericity, significant levels were adjusted using the Greenhouse-Geisser correction when performing repeated-measures ANOVA, and all the effect sizes are reported as partial eta-squared (η_p^2) or Cohen's *d*, when appropriate.

EEG recordings and preprocessing

The EEG data were recorded with a sampling rate of 1024 Hz from 64 scalp electrodes. Two additional electrodes were placed in the outer canthi of each eye to measure horizontal eye movements (HEOG). All data were collected using a BioSem Active Two system (see www.biosemi.com for details). Data were preprocessed with the EEGLAB toolbox for Matlab (Delorme & Makeig, 2004).

The data were high-pass filtered offline at 0.5 Hz and re-referenced off-line to the scalp average. After baseline subtraction (-200 to 0 ms pre-stimulus base line), trials with muscle and blinking artifacts during the stimulus were visually identified and manually removed (average of 7%). Then, additional artifacts or any kind of noise not related with brain activity were removed using independent component analysis in EEGLAB (Delorme & Makeig, 2004). All the EEG analyses involved only correct trials.

SSVEP analysis

We performed two sets of analyses on the SSVEP data for each of the flickering frequencies used in the experiment: "static SSVEP", in which the fast-Fourier transform (FFT) was computed over the full time window of each trial (0 to 2000 ms), and "dynamic SSVEP", in which a narrow band-pass Gaussian filter was applied to inspect the time-varying changes in SSVEP amplitude. Whereas the former method provides higher frequency resolution and increases the SNR characteristics, the latter method provides higher temporal precision and thus the ability to detect time-varying changes in SSVEP amplitude resulting from phasic tasks events. The time windows for analysis were applied equally to all conditions.

SSVEP was extracted using a spatial filtering method termed rhythmic entrainment source separation (RESS; Cohen & Gulbinaite, 2017). The RESS method involves using generalized eigendecomposition to construct an optimal spatial filter that maximizes the SSVEP effect. The eigenvector with the largest eigenvalue maximally differentiates two covariance matrices (a "signal" and a "reference" covariance matrix), and that vector is used as channel weights to combine data from all electrodes. The signal covariance matrix was obtained from the narrowband-filtered signal at each stimulus frequency. The reference covariance matrix was obtained from data filtered at the closely spaced up- and down-neighbor frequencies. Importantly, the spatial filters were computed per frequency pooling data across all conditions; thus, although the spatial filter maximizes the overall SSVEP amplitude, there is no potential for biasing any condition comparison. The power spectrum was computed via the FFT for each flicker condition (15 Hz, 20 Hz, 24 Hz and 17.14 Hz) pooling over magnitude and congruency conditions over the entire trial time window. The static SSVEP was computed as the SNR as the ratio of the power at the flickered frequency to the average of neighboring frequencies surrounding each frequency (± 2 Hz, excluding a 0.5 Hz window around each center frequency) allowing us to convert power spectrum into SNR units to facilitate comparability across groups. See Figure 3.1 in chapter 3 as an example of the topographical maps and SNR spectra obtained with RESS spatial filter.

For the computation of the dynamic SSVEP amplitudes, a narrow-band Gaussian filter was implemented for each of the flicker conditions with a full width at half-maximum (FWHM) of 6 Hz (the standard deviation of the filter; while a narrow filter provides better spatial precision the temporal precision is reduced, therefore we use a high FWHM to increase the temporal resolution of the filter). This Gaussian was point-wise multiplied by the power spectrum of the EEG data, and the inverse Fourier transform was applied to reconstruct the time course of the activity (i.e., convolution). After filtering the data, the amplitude of the frequencies of interest was extracted as the square magnitude of the result of the Hilbert transform. We call this time series the "SSVEP amplitude time series". To facilitate comparisons across subjects, the SSVEP time series were baseline-normalized to a pre-stimulus period of -600 to -200 ms. Note that in our task the flickering stimulus was present all the time, including the peri-stimulus period, thus the baseline was computed using the average of all conditions within each frequency, allowing for detection of possible condition differences at peri- and post-stimulus activity. Baseline normalization allows rescaling the activity relative to the selected baseline, which facilitates comparison between frequencies (Cohen, 2014).

SSVEP statistical analysis

An initial visual inspection of the SSVEP results was performed for all the subjects and all the four flickering frequencies (15 Hz, 20 Hz, 24 Hz and 17.14 Hz) to confirm the SSVEP effects of the experimental paradigm. However, the statistical analyses were performed for the flickering stimuli closer to the fixation point (20 Hz and 24 Hz), first, because the analyses were focused on observing differences between the different experimental conditions and not between different flickering frequencies, and these two frequencies were optimal for further analysis; second, after performing initial analyses we didn't observed significant effects for the 15 Hz and 17.14 Hz, and finally, because these two frequencies were used as control conditions for the attention-modulation effects on the task. The SNR analyses for the differences between conditions were tested using repeated-measures ANOVA with factors number magnitude (small and large), frequency (20 Hz and 24 Hz) and congruency (target side: left or right). In order to detect time-varying changes in SSVEP amplitude resulting from phasic task events, statistical analyses of the EEG SSVEP amplitudes time series were implemented for these eight experimental conditions (number magnitude, flicker and target side). Because the flicker was continuous in our task, first we pooled the data by target side presentation and frequency according to the side where the flicker was displayed (i.e., 20 Hz on the left and 24 Hz on the right) to evaluate whether each flicker frequency deviates from 100% (i.e., baseline), and then we performed the same analyses separately for each frequency and condition specific to test whether there were significant differences between conditions. Nonparametric permutation testing was used in combination with cluster correction to evaluate condition differences in dynamic SSVEP over time (Maris & Oostenveld, 2007). To create a distribution of null-hypothesis time courses, the difference of the congruent – incongruent conditions for each frequency and number magnitude factor, for each subject was computed, and then multiplied this condition difference for a random subset of subjects by -1 (which is equivalent to randomizing incongruent – congruent vs. congruent – incongruent). This was repeated for 1,000 iterations. Finally, cluster correction was implemented to correct for multiple comparisons over the all-corresponding time points of the selected time window with a threshold value for pixel and cluster-levels of p = .05.

RESULTS

Behavioral results

Here we report only the relevant significant ANOVA results; see Table 5.1 for descriptive statistics and additional inferential statistics. Results for RTs showed significant effects for the interaction between number magnitude and congruency ($F(1,22) = 19.84$, $p < .000$, $\eta_p^2 = .474$). In particular, participants were faster detecting targets displayed on the right when preceded by large magnitude numbers as compared with targets displayed on the left preceded by large magnitude numbers. Although ANOVA results described a significant interaction between numbers magnitude and congruency (side of target presentation and the preceding number), this effect was not observed for targets displayed on the left and preceded by small numbers. In this particular case the RTs were longer for the congruent conditions as compared with the incongruent conditions; targets displayed on the right were detected faster when preceded by small numbers (Figure 5.2a). We did not obtain any significant effects for the remaining factors (all *p*'s > 1), however.

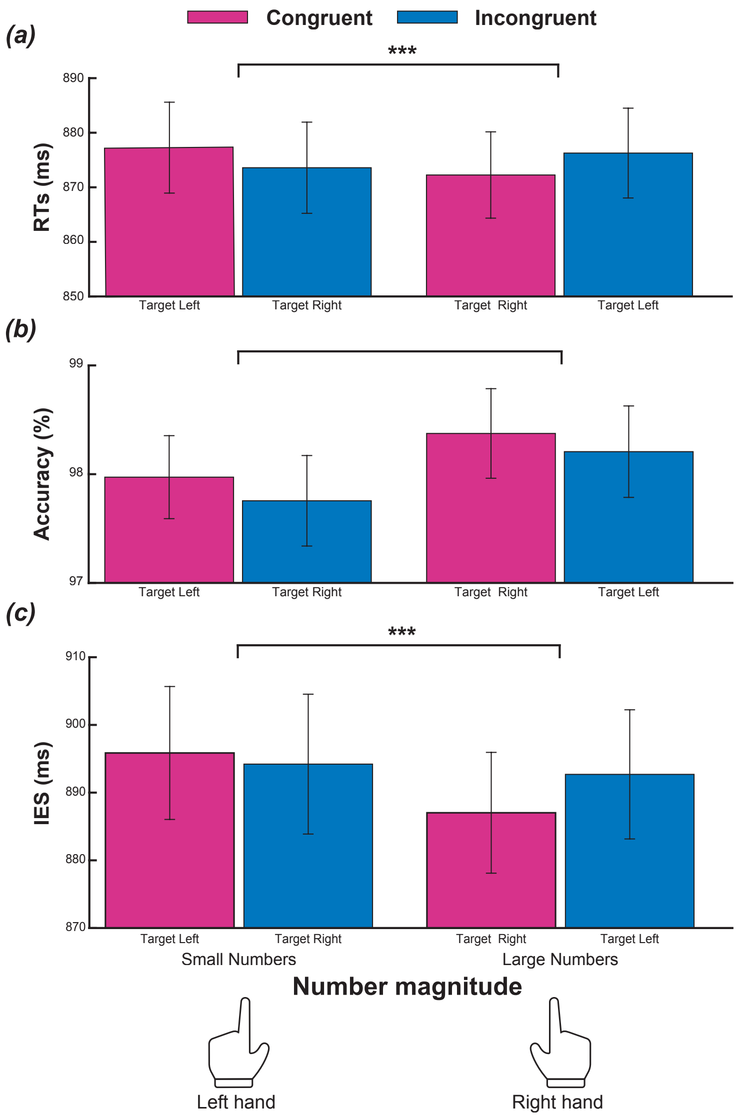


Figure 5.2. Behavioral results for the target detection task. (a) Shows the RTs, (b) accuracy and (c) the Inverse Efficiency Score (IES) obtained for the different conditions. For a description of the IES methods, see page 109. Error bars represent standard error of the mean. *** $p < .001$

For all the conditions accuracy was above 95%. However only a significant borderline effect was observed for the congruency factor (*M* = 98.2, *SE* = 0.37 and *M* = 97.9, *SE* = 0.39; $F(1,22) = 4.16$, $p = .053$, $\eta_p^2 = .159$) meaning that participants were more accurate detecting targets on the left/right when small/large numbers preceded them, respectively. The results for the effects of number magnitude factor and the interaction between congruency and number magnitude were not significant (all *p*'s > 1) (Figure 5.2b).

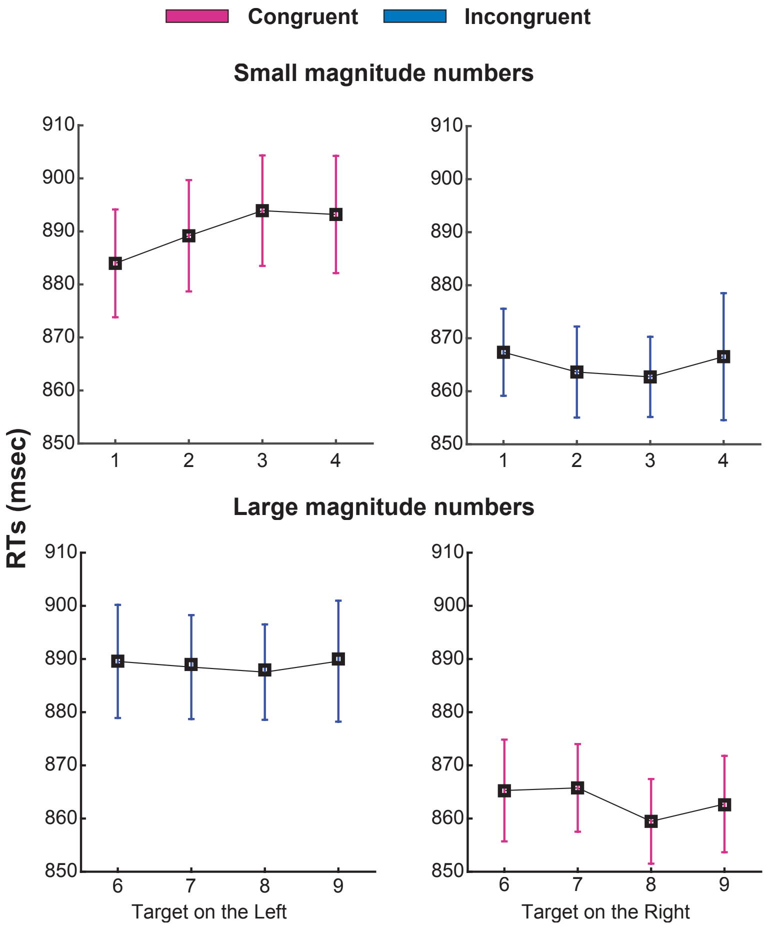


Figure 5.3. Individual performance per number magnitude. If the hypothesis of automatic shift in spatial attention were true we would expect faster reaction times for congruent conditions: targets on the left preceded by small numbers (upper-left) and targets on the right preceded by large numbers (bottom-right) as compared to the incongruent conditions. However, this was true only for targets presented on the right and preceded by large numbers, while for the congruent conditions with small numbers there was not such effect. Error bars represent standard error of the mean.

Because the observed variability obtained in the behavioral performance (i.e., RTs and accuracy), to allow a better comparison between results we analysed the inverse efficiency score (IES) in [ms]. In the IES the [..] indicates that these values have a temporal dimension and incorporate a correction for accuracy. The IES combines both behavioral measures (RTs and accuracy) in a single performance and is calculated as the median RT divided by the proportion of correct responses in each condition (Bruyer & Brysbaert, 2011). The IES is a standard way to integrate accuracy and RTs into a single dependent variable that has been previously reported in SNARC studies (Weis, Estner, Krick, Reith, & Lachmann, 2015; Weis et al., 2016).

Table 5.1. Descriptive statistics and ANOVA from behavioral results.

		RTs (ms)		Accuracy (%)		IES (ms)	
Number magnitude	**Congruency condition**	**Mean**	***SD***	**Mean**	***SD***	**Mean**	***SD***
Descriptive statistics							
Small	Congruent	877.27	39.94	97.97	1.83	895.85	47.08
	Incongruent	873.59	40.07	97.75	1.99	894.21	49.53
Large	Congruent	872.25	37.92	98.37	1.97	877.02	42.78
	Incongruent	876.27	39.47	98.21	2.02	892.70	45.74

Variable	***df***	***F***	***p****	**ε ****
Repeated measures ANOVA for RTs				
Number magnitude	1	.225	.640	.010
Congruency	1	.057	.813	.003
Number magnitude X Congruency	1	19.845	.000	.474
Repeated measures ANOVA for accuracy				
Number magnitude	1	2.598	.121	.106
Congruency	1	4.164	.053	.159
Number magnitude X Congruency	1	.144	.708	.007
Repeated measures ANOVA for IES				
Number magnitude	1	1.712	.204	.072
Congruency	1	2.614	.120	.106
Number magnitude X Congruency	1	10.382	.004	.321

Note: Upper table contains the descriptive statistics for RTs, accuracy and Inverse Efficiency Score (IES). Middle and bottom tables contain the ANOVA results for RTs, accuracy IES, respectively. *SS* = sum of squares; *MS* = mean square. **p* < .05 ** *ε = Epsilon Greenhouse-Geisser correction*.

Repeated measures ANOVA with factors number magnitude and congruency showed significant effect for the interaction between number magnitude and congruency ($F(1,22) = 10.38$, $p = .004$, $\eta_p^2 = .321$), confirming a positive effect of presentation of large magnitude numbers before targets were displayed on the right side (Figure 5.2c); no significant effects were obtained neither for the number magnitude nor the congruency factor (all *p's* > 1). These results are consistent with the results obtained for RTs (Figure 5.2a).

Finally, given the observed variability in the behavioral results we analysed the individual responses for small and large magnitude numbers according to the target presentation. Repeated measures ANOVA with factors number magnitude (1,2,3,4,6,7,8,9) and target presentation (left/right) showed significant effect for the target presentation factor ($F(1,22) = 24.414$, $p < .000$, $\eta_p^2 = .526$). This result is consistent with the accuracy borderline effect we observed and shows that, although magnitude is activated, it does not have an effect on improving the detection of peripheral targets; therefore, we can conclude number magnitude did not induce the so-called SNARC effect in our task (Figure 5.3). Table 5.1 lists all the ANOVA and descriptive statistics for RTs, accuracy and IES the behavioral data.

EEG results

SNR results

For all EEG SSVEP analyses we focused on the closest flicker frequencies to each side of the fixation point to the left (20 Hz) and to the right (24 Hz) (see Methods). The SNR spectra exhibited robust peaks at both of these flicker frequencies indicating that the design of our experiment was appropriate to elicit robust SSVEP effects.

The group average showed RESS topographical maps with high SNR at posterior sites in the right hemifield for the 20 Hz flicker displayed in the left visual hemifield and to the left hemifield for the 24 Hz flicker displayed in the right visual hemifield. And high power spectrum at the corresponding frequencies was also observed in the group average for both experimental conditions: congruent and incongruent (Figure 5.4).

Our main hypothesis was that the observation of numbers would induce the *SNARC-spatial attention effect*. Therefore, we expected to observe higher SSVEP SNR for congruent conditions, this is, trials where small numbers preceded targets on the left side and large numbers preceded targets displayed on the right side. Repeated-measures ANOVA (with factors number magnitude and congruency) showed significant main effects for the number magnitude ($F(1,22) = 6.213$, $p = .021$, $\eta_p^2 = .220$) factor. Neither the congruency nor the interaction between number magnitude X congruency showed significant results (all $p > .1$). Figure 5.5 shows bar plots of the SNR for the left (20 Hz) and right (24 Hz) flicker. Table 5.2 contains all the ANOVA results of the SNR for the left and right flicker.

Dynamic SSVEP results

The static SSVEP exhibited high SNR, but it is possible that the shift in spatial attention was transient, and therefore it might the reason why, despite the observed SNR differences between congruent and incongruent conditions, the congruency and the interaction between number magnitude and congruency (side of the target presentation) were not statistically significant and not have been very clear in the static analysis, which requires a long time window for spectral resolution. Therefore, we applied a dynamic SSVEP amplitude analysis to search for temporally localized modulations. Our key hypothesis was that just by observing numbers when they are not relevant for the task would produce the *SNARC-spatial attention effect*; meaning that numbers' magnitude would be automatic activated inducing an *automatic shift of spatial attention* according to their mental representation in the MNL. Thus, we expected SSVEP amplitudes to be higher relative to baseline, and specifically being higher for congruent conditions

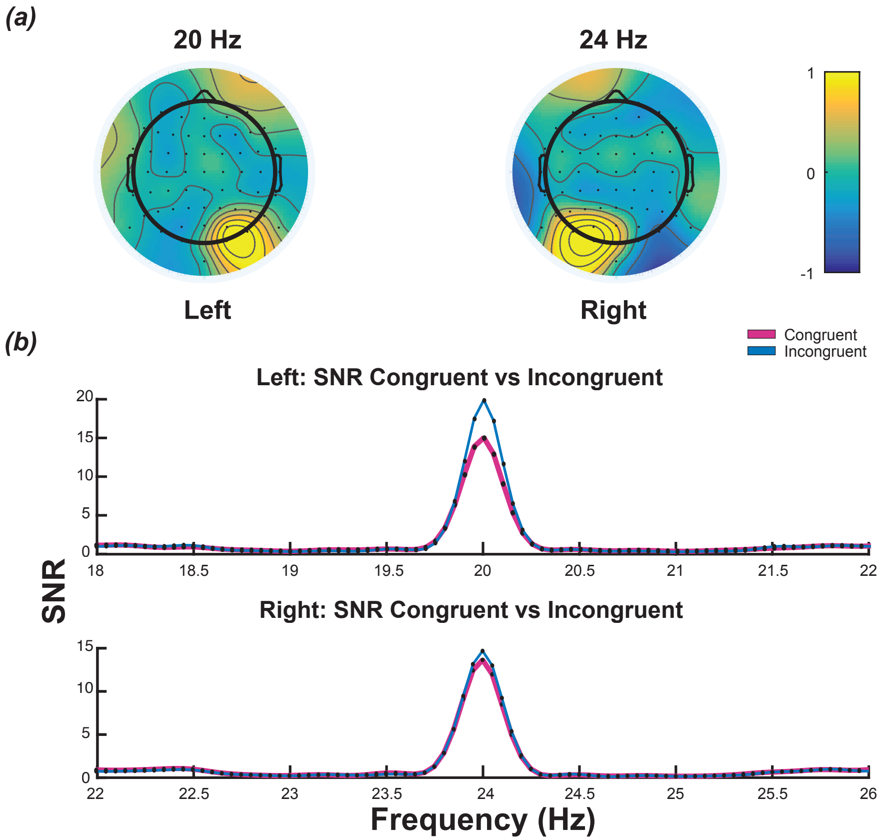


Figure 5.4. Group average SSVEP response. Upper panel (a) shows the topographical maps obtained across subjects. And panel (b) shows the average SNR response per frequency on each condition. Values in the *y* axis correspond to converting power spectrum to SNR units.

Similar to our previous study (i.e., parity task, chapter 4), to facilitate comparison between frequencies we performed the percentage change baseline normalization to a pretrial baseline of -600 to -200 ms (See Methods). Because the flicker was continuous over time and any change from the baseline is relevant we initially pooled all the conditions by number magnitude and congruency factors to evaluate whether the SSVEP amplitudes deviates from 100 % (i.e., baseline). Therefore we performed a *t*-test for the difference between every time point from each of the flicker condition against 100 (all *p* values < .05, cluster-corrected for multiple correlated tests over time points).

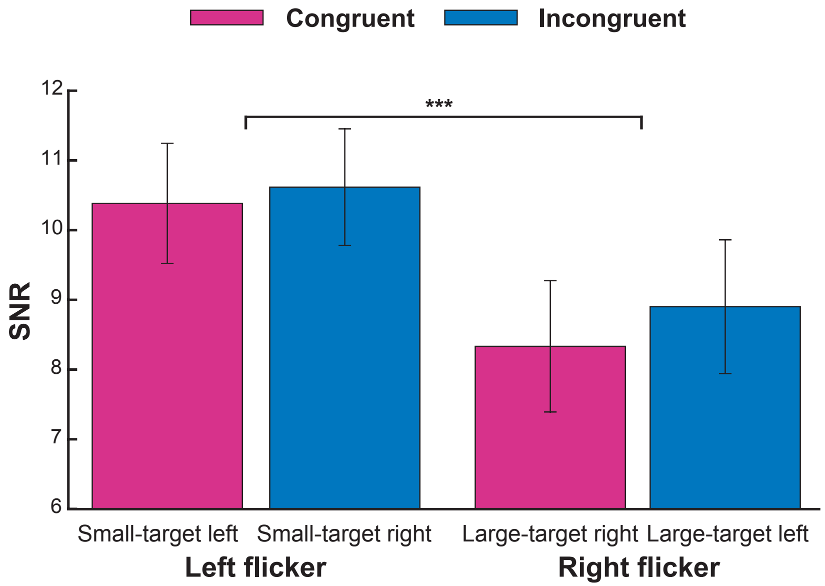


Figure 5.5. Statistical main effects were obtained for the number magnitude factor for the SSVEP SNR in the incongruent (small/large numbers preceding right/left target presentation, respectively). (a) SNR for left visual hemifield (b) SNR for the right visual hemifield. Values in the *y* axis correspond to converting power spectrum to SNR units. Error bars represent standard error of the mean. **p* < .05

Table 5.2. ANOVA for the SNR results.

Variable	*df*	*F*	*p**	ε **
Repeated measures ANOVA for SNR				
Number magnitude	1	6.213	.021	.220
Congruency	1	1.357	.256	.058
Number magnitude X Congruency	1	.193	.665	.009

Note: SS = sum of squares; *MS* = mean square. **p* < .05 ** *ε = Epsilon Greenhouse-Geisser correction*.

For the left flicker congruent conditions a significant change in the SSVEP amplitude with respect to the baseline was observed from -397 ms before stimulus onset to 979 ms after stimulus onset. From this time point the SSVEP amplitude was below the baseline. For the left flicker congruent conditions a statistically significant time window between 460 and 855 ms was observed. Additionally, two more time windows showed statistical differences with respect to the baseline, but those time windows were observed below baseline meaning that such differences were between the baseline and the non-SSVEP significant changes in amplitude (Figure 5.6a). For the left flicker incongruent conditions the significant changes in the SSVEP amplitude was observed -361 ms before stimulus onset and 978 ms after stimulus onset. And after returning to the baseline no more significant changes in the amplitude were observed. And one statistically significant time window between 427 and 613 ms was observed. Similar to the congruent conditions, time windows showed statistical differences wit respect to the baseline but those time windows were observed below baseline. Notice that there are two observed significant time windows for the congruent conditions before time 0 (stimulus onset) that correspond to the baseline used for normalization (Figure 5.6b).

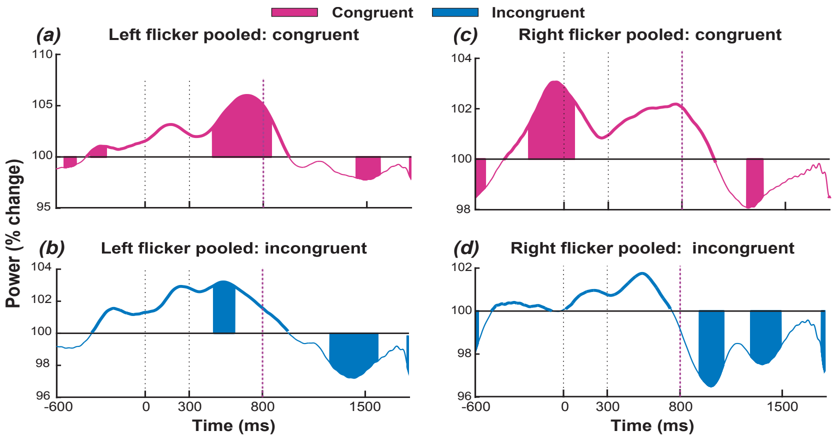


Figure 5.6. SSVEP changes in amplitude during the target detection task for the left (a, b) and right (c, d) visual hemifield flicker stimuli for the congruent (a, c and incongruent (b, d) conditions. Thicker lines represent when changes are above zero from baseline and thinner line represent changes below baseline. *y* axis corresponds to SSVEP percentage change amplitudes. Shaded area represents statistically significant differences between conditions. Dotted line at time 0 represents time stimulus onset (number presentation), dotted line at 300 ms represents the time stimulus offset and dotted line at 800 ms represents target presentation. $p < .05$

For the pooled right flicker congruent conditions significant change for the SSVEP amplitude was observed from -402 ms before stimulus onset to 1017 ms after stimulus onset. And one statistically significant time window difference from baseline was observed between -263 ms before stimulus onset to 62 ms after stimulus onset. And another significant time window was observed between 1240 and 1347 ms, however this window was below the baseline (Figure 5.6c). The incongruent conditions for the right flicker showed a significant increasing of the SSVEP amplitude from -14 ms before stimulus onset to 749 ms after stimulus onset when the difference in amplitude reaches the baseline. For the incongruent conditions there were not statistically significant time windows between the baseline and the significant changes in amplitude. And three different time windows between the baseline and the SSVEP changes in amplitude below the baseline were observed (Figure 5.6d).

In order to elucidate whether the magnitude of the number was related with the SSVEP changes of amplitude we performed the dynamic SSVEP analysis over the different conditions. Thus, for each flicker condition we evaluated the effects of the number's magnitude (i.e., small or large) according to the side of target presentation (i.e., left and right), therefore we compared the congruent vs. the incongruent conditions for each flicker frequency. Similar to the previous analyses, we performed the nonparametric permutation testing with cluster correction to evaluate condition differences in the dynamic SSVEP over time for the left (20 Hz) and right (24 Hz) flicker frequency. For these dynamic analyses we create the distribution of the null-hypothesis from the difference of the congruent – incongruent conditions (See Methods) instead of using the baseline (i.e., 100%) subtraction we implemented for the pooled dynamic SSVEP analysis. All p values < .05, cluster-corrected for multiple correlated tests over time points.

For the difference between congruent vs. incongruent no significant differences were obtained, neither for the flicker stimulus in the left hemifield where small magnitude numbers would allocate spatial attention to improve target detection for targets displayed on the left, nor the flicker in the right hemifield where large magnitude numbers were expected to allocate spatial attention to the right to improve detection of targets displayed on the right, according to Fischer's proposal. As mentioned above, notice that the observed changes before time 0 correspond to the baseline time window used for normalization (Figure 5.7).

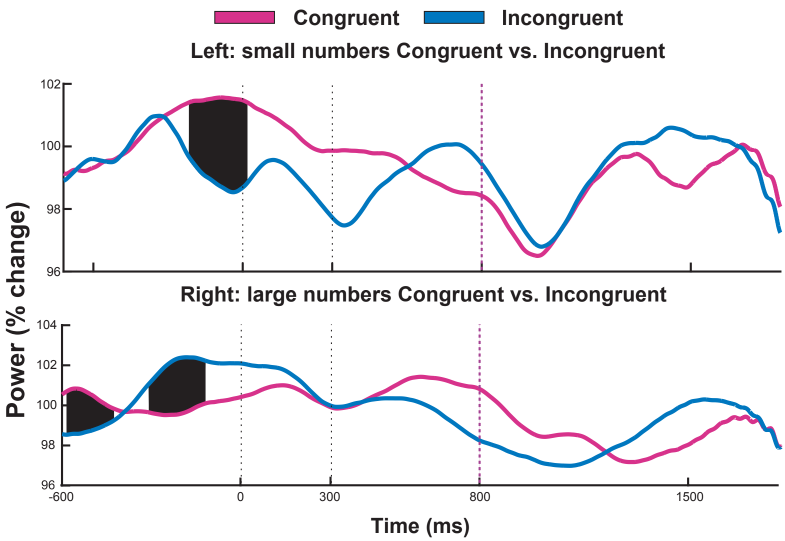


Figure 5.7. Dynamic SSVEP for the left visual hemifield flicker stimuli (20 Hz, upper panel) the right visual hemifield flicker stimuli (24 Hz lower panel). Arrangement in Fig 5.7 is the same as in Fig 5.6. Shaded areas represent statistically significant differences between conditions. $p < .05$

DISCUSSION

In our previous experiment we obtained EEG SSVEP evidence for the allocation of spatial attention induced by numbers during the parity task where numbers were relevant for the task but not their magnitude. In the present follow-up, we wanted to evaluate whether the simple observation of numbers, when they are not relevant for the task, would have an effect on allocating spatial attention as proposed by Fischer et al. (2003). To do so, we implemented Fischer's task where numbers preceded the presentation of peripheral targets while different nonrelevant flicker stimuli were constantly displayed on each side of the fixation point (where numbers were presented). The statistical analysis of the RTs showed significant effects for the interaction between number magnitude and congruency, meaning that, if number's mental representation (e.g., MNL, SRC) and side of the target presentation shared the same spatial position (i.e., small numbers/left targets and large numbers/right targets), this would benefit the behavioral performance. Nonetheless, in our results this was true only for trials where large magnitude numbers preceded targets displayed on the right visual hemifield while targets on the left visual hemifield preceded by small numbers did not show such benefit for the RTs, going in a different direction with Fischer's results. Additionally, the behavioral results for accuracy were not consistent with the RTs and, on the contrary, the IES confirmed the obtained results for the RTs. This variability in the behavioral results allows to conclude that we could not replicate Fischer's results, and as previously reported we cannot confirm neither the so-called SNARC (Bonato et al., 2009) nor the SNARC-spatial attention effect (Casarotti et al., 2007; Fattorini et al., 2015; Jarick et al., 2009; Ranzini et al., 2009) in our task.

Although our behavioral and SSVEP results are consistent between them the results do not provide evidence consistent with the behavioral data reported by Fischer et al. (2003). However, it is worth mentioning two important aspects regarding our results and previous reports providing evidence about the SNARC effect given that we did not observe a general SNARC effect but we did observe a positive interaction between target detection and large magnitude numbers presented before targets displayed on the right. First, the different analyses we performed for the behavioral results showed a benefit in performance for targets displayed on the right and preceded by large magnitude numbers, which is consistent with the so-called SNARC effect. However, this space-magnitude interaction was not observed for targets on the left preceded by small magnitude numbers, therefore we cannot confirm a SNARC effect in our target detection task. This inconsistency in performance between targets in the left and right, and small and large numbers preceding them, respectively, points in a different direction as described by Fischer et al. (2003) but we cannot completely rule out the interaction between mental representation of numbers and space since we obtained significant results for some task conditions at the behavioral and physiological level. Second, only the pooled left flicker congruent condition showed significant SSVEP differences between the baseline and the changes in amplitude (Figure 5.6).

However, no significant differences were observed when obtaining the difference between congruent and incongruent conditions (Figure 5.8). These SSVEP differences between both the congruent and incongruent conditions showing no indication of effect arising neither during the perceptual nor the representational processing stage are consistent with previous reported by Keus, Jenks, & Schwarz (2005) and Keus & Schwarz (2005), describing a cognitive processing of numbers magnitude in our task.

Consistent with our behavioral results, the SSVEP difference between congruent – incongruent conditions showed an attention modulation effect for incongruent conditions for the flicker stimuli on the left hemifield and for the congruent conditions for the flicker visual stimuli on the right. This means that for both flicker conditions when the target was presented on the right hemifield attention was already displayed towards the right space independently of the magnitude of the number preceding it. Our initial goal was to provide physiological evidence for the automatic allocation of spatial attention induced by observation of numbers according to their representation in the MNL as Fischer and colleagues proposed. However, this was not the case in our experiment and on the contrary the interaction between numbers and space mental representation did not show a direct effect on the SSVEP amplitude as expected by the MNL theory.

Nonetheless, an emerging effect of numbers' magnitude was observed for the large numbers over the right visuospatial space, meaning that, although these results are inconsistent with the MNL it cannot be excluded that passively viewing of numbers create a spatial context where the semantic processing of numbers is elicited (Fias & Fischer, 2004b). While in our previous experiment where numbers were relevant for the task we observed this number semantic activation of magnitude having an effect on spatial attention according to the MNL, in the present study such activation and effect is not complete clear. Hence, our results could be better explained by the hypothesis that perception of digits would activate the spatial representation of number (Salillas et al., 2008) but not strictly represented in a MNL (Goffaux et al., 2012). Specifically, since we observed a general deployment of spatial attention towards the right visual hemifield we considered that the role of numbers perception could be better explained by the effect induced by the spatial salience of the response (participants hold the mouse in a body-centered reference frame) and the overlapping of the semantic number activation induced by the task, seemingly more in a positive " +" and negative "-" way (Proctor & Cho, 2006). Thus, because large and even numbers have a positive mental representation according to the polarity correspondence theory of compatibility (Proctor & Cho, 2006; PCT) this would explain the observed response in the visual areas corresponding to responses in the hemisphere contralateral to the fixation point, being consistent with previous reports of contralateral activation of the early visual areas (Deutschländer et al., 2005), in our case particularly to the right visual hemifield.

The EEG and behavioral data we obtained are consistent with previous reports suggesting a hemispheric specialization and contralateral response to stimulus presentation providing evidence for the feasibility of using the SSVEP as technique to study numbers' mental representation and their relation with allocation of spatial attention. First, as Harvey, Kelin, Petridou, & Dumoulin (2013) reported in an fMRI study where superior parietal cortex activity of the right hemisphere was associated with topographical representation of small magnitude numbers, we observed topographical maps response contralateral to the side of flicker stimuli being right posterior for the left visual hemifield and left posterior for the right visual hemifield. Second, because in our task the flicker stimulus was present during the complete task our SSVEP results showing a leftward, rightward SSVEP response are in line with previous observations regarding the neuroanatomical allocation of visuospatial attention (Huddleston & DeYoe, 2008).

Finally, although we did not obtain direct physiological evidence for the SNARC-spatial attention effect in our study, we did observe an interaction between numbers mental representation and allocation of spatial attention. It is worth mentioning that this interaction would possibly reflect a spatial attention effect as has been mentioned in several studies previously (see Introduction) with a physiological component similar as we described with our previous study (see Chapter 4), but possible that effect is happening at small local level that we could not measure with the EEG. Therefore, as we mentioned above, we cannot rule out the effect that numbers have in spatial attention when they are part of the environment where we are performing a spatial task.

CONCLUSION

Overall, in the present study the expected results for the congruent conditions pointed in an opposite direction as previously reported. We have demonstrated that passively observing numbers do not induce and automatic shift of spatial attention, the so-called SNARC-spatial attention effect, therefore centrally presented cue-numbers do not favor the detection of lateral presented targets following their presentation. However, it should be stressed that the physiological evidence we obtained shows that number semantic is activated during the task and is consistent with previous studies supporting the hypothesis that magnitude processing arises in the parietal cortex (Holloway, Price & Ansari, 2010; Ranzini et al, 2009) where large magnitude numbers modulates the visuospatial attention effects as we observed for incongruent conditions. Finally, our study contributes to further understand the interaction between number magnitude, mental representation of space and the physiology of the SNARC effect.

ACKNOWLEDGEMENTS

A. M. C. is funded by Departamento Administrativo de Ciencia, Tecnología e Innovación, Colciencias call 529/ 2011 (Colombia). M. X. C. is funded by an ERC-StG 638589. R.G. is funded by an ERC awarded to Dr. Rufin Vanrullen (CerCo institute, Tolouse, France).

DECLARATION OF INTEREST STATEMENT

The authors declare that there are no conflicts of interests.

AUTHOR CONTRIBUTIONS

M.X.C. and R.G. conception and design of research; M.X.C. analysed data; A.M.C. performed experiments; analysed data; M.X.C. and A.M.C. interpreted results of experiments; A.M.C. prepared figures; drafted manuscript; A.M.C., M.X.C. and R.K.R. edited and revised manuscript; M.X.C. and R.K.R. approved final version of manuscript.

Chapter 6

Summary and general discussion

SUMMARY

Daily activities require our brain to selectively attend to aspects of the environment that are most relevant to guide and monitor our behavior and to avoid undesirable outcomes of our and other's actions. Because prioritizing and processing relevant information may be highly demanding, and thus difficult to maintain at all times, our brain needs to properly select and filter different features (e.g., based on location, physical features such as color or shape, or time of occurrence) and adjust our cognitive control system, among others, so that our behavioral performance corresponds to the requirements of each particular situation.

To understand how our brain selects and processes information to generate a proper response is one of the goals of cognitive neuroscience. To this end, several techniques have been implemented for studying cognitive processes, such as attentional processing, cognitive control and temporal predictability, among which we note behavioral testing and noninvasive electrophysiological recording. Because cognitive processing can be deployed and can change rapidly (within a fraction of a second), brain-imaging techniques with high temporal resolution are particularly useful for studying the aforementioned cognitive processes. Electroencephalography (EEG), with a temporal resolution in the order of milliseconds, is one of the most widely used brain-imaging tools for studying human cognition among which the steady-state visual evoked potential (SSVEP) is a commonly used technique.

The SSVEP technique involves repeatedly flickering visual stimuli while measuring their EEG response on the scalp. As the visual stimulus flickers (like a strobe light), the activity of large neural populations in the brain's early visual processing areas will resonate at the same temporal frequency, and leads to a sinusoidal EEG response called SSVEP (Regan, 1989). The SSVEP has been extensively used to study visual attention because its amplitude correlates with the amount of attention paid to the flickering stimulus. Although changes in SSVEP amplitude are generally related to the effects of attention, Ding et al. (2006) suggested that the attention modulation may depend on stimulation frequency and that for frequencies in the lower alpha band (8 – 10 Hz) an increase in SSVEP amplitude can be found when the flickering frequency is peripheral to the attended target.

In the present thesis, I report on the SSVEP to study temporal attention and the relation between spatial attention and mental representation of numbers.

First, because understanding the cognitive and biological aspects of cognition in healthy as well as in clinical populations would extend our knowledge about such processes, and in order to aid in development of solutions that could benefit

clinical populations, I presented in **chapter 2** a comprehensive review of Brain-Computer Interfaces (BCIs). BCI systems enable a user to communicate with the external world by directly translating his/her brain activity into (computer) commands without relying on the brain's normal output pathways. The review is presented in the context of language model applications that supplement non-invasive BCI-based communication systems. The review offers an overview of the advantages and challenges when implementing language models combined with different techniques, including the use of SSVEP, in BCI-based communication systems when implemented in conjunction with other Ambient Assisted Living (AAL) technologies.

To the best of my knowledge, SSVEP has not been used to study temporal attention. This is important because temporal predictability has been shown to improve attention and sensory processing across different domains (Woodrow, 1914). The relevance of SSVEP to study temporal attention is important to demonstrate for fundamental scientific reasons but also for future diagnostic ones since temporal attention and the correct use of temporal cues to guide behavior are impaired in several clinical disorders including Parkinson's disease (Rochester et al., 2005) and Schizophrenia (Silberstein et al., 2000). In the research lab, temporal attention is often studied as attention to the moment a particular stimulus appears or disappears from the screen (Babiloni et al., 2004). Several ERPs (e.g., Miniussi, Wilding, Coull, & Nobre, 1999) and oscillatory studies (e.g., Klimesch, 2012) have been implemented to study temporal attention. Neural oscillations in the alpha band (~10 Hz) seem to be part of the substrate of temporal attention. One of the theories about temporal attention proposes the existence of internal oscillators whose attentional pulses can be entrained to environmental rhythmicity to enhance stimuli processing at predictable times (Mathewson, Fabiani, Monica, et al., 2010), where temporal expectancies are phase locked to ongoing brain oscillations to improve target recognition when time intervals are predictable (Schroeder & Lakatos, 2010).

We designed a first experiment to evaluate whether SSVEP stimulation and its temporal dynamics can be used to study temporal attention, and to evaluate whether attention-modulation of SSVEP is similar for three different frequencies (**Chapter 3**). Because temporal expectancies allow maximal target recognition at predictable times to have an effect on the participant's response, we manipulated the Inter stimulus interval (ISI; constant versus variable) to evaluate whether there is an effect of SSVEP stimulation on behavioral performance. The obtained behavioral results replicated previous studies confirming the benefits of temporal expectations on performance for trials with constant ISI. EEG analyses revealed robust SSVEP amplitudes for all flicker frequencies, although a main effect of temporal expectations on SSVEP amplitude was not significant. Additional analyses revealed temporal predictability-related modulations of SSVEP amplitude at 10 Hz and its second harmonic (20 Hz), and for the 6 Hz flicker but not for 15 Hz, for any ISI condition. These results provide some evidence for the feasibility of the SSVEP technique to study temporal attention for stimuli with flicker frequencies around the alpha band.

Another important component of attention is the ability to direct attention in the visual field to a particular stimulus while suppressing the processing of competing stimuli in other locations, called spatial attention. The representation of numbers in the brain is spatially organized on what is known as the mental number line. The Spatial-Numerical Association of Responses Codes (SNARC) effect describes the relationship between the spatial representation of numbers in the brain and the number magnitude (S Dehaene et al., 1993). It has been used to explain a participant's reaction time in a parity judgment task. The magnitude of the number in the mental number line leads to faster responses when the digit's position is congruent with the response hand. This interaction between mental representation of numbers and enhancement of behavior has been described in tasks where the number magnitude is relevant for the task (magnitude-judgment) but also when the magnitude information is not task-relevant (parity judgment; Fias & Fischer, 2004; Fias, Lauwereyns, & Lammertyn, 2001).

The studies on spatial attention and mental representation of numbers reported in this thesis involved modified versions of the SNARC task. The purpose was to use the SSVEP technique to provide direct evidence (or lack thereof) for the hypothesis that SNARC induces spatial shifts of attention. This is a novel approach for studying number processing and its effect on the allocation of spatial attention. Previous EEG studies on spatial attention during covert attention shifts provide evidence of changes in SSVEP amplitude at posterior and contralateral locations for target detection compared to non-attended flickering stimuli (M. M. Müller & Hillyard, 2000). Because attentional shifts can be achieved without moving the eyes −covert attention in which participants keep their gaze at the fixation point while the stimulus is displayed either to the left or to the right hemifield of the fixation point−, we implemented a modified Fischer's et al. (2003) task. In a covert spatial attention task participants are asked to fixate the center of the screen while detecting a target displayed either to the left or the right side of the fixation point. For each trial, but before target presentation, one out of four digits were displayed and participants were informed that the numbers were not relevant to the task.

The results of the parity judgment task (classify numbers as odd or even while ignoring their magnitudes) described in **chapter 4** replicated the expected behavioral patterns predicted by the SNARC effect. We also observed significant changes in the SSVEP amplitude with respect to the baseline for the left and right flickering stimuli, for both the congruent and incongruent conditions. Statistically significant differences between the congruent and incongruent conditions were larger for the congruent conditions for the flickering stimulus on the left. Taken together, these findings support the hypothesis that, when numbers are part of the task but their magnitude is not relevant, the SNARC-spatial attention effect is elicited as a cognitive effect resulting from the mental representation of numbers and its relation with the space representation, more so than merely a motor effect. Results of the target detection task (detection of peripheral presented targets while ignoring numbers that were not relevant for the task) in **chapter 5** showed benefits for the interaction between large magnitude numbers preceding targets presented in the right hemifield, providing a partial replication of the SNARC behavioral effect. And EEG SSVEP results showed an attention modulation effect for the difference between congruent and incongruent conditions, showing larger SSVEP amplitudes for incongruent conditions (small numbers/targets on the right) for the flickering stimuli in the left hemifield and for the congruent conditions (large numbers/target on the right) for the flickering stimuli in the right hemifield. Our results demonstrate that passively observing numbers does not induce an automatic shift of spatial attention, or at least not an effect that could be measured electrophysiologically. They also demonstrate that even when numbers are irrelevant for the task, number semantic representation is activated.

Together, the results presented in this thesis provide, on the one hand, supporting evidence for language models within BCI systems, as a significant improvement in spelling performance can be achieved, opening new avenues for BCI integration in the AAL community and for rehabilitation. On the other hand, the results reported here contribute to a better understanding of the psychophysiological components of temporal and spatial attentional processing, the relation between flickering frequencies and endogenous brain oscillations, and the relation of these endogenous brain oscillations with information processing, cognitive control and behavioral performance. Additionally, for all studies presented in this thesis, I provide important evidence for a future implementation of the SSVEP technique to study temporal attention and the role of number inducing automatic shifts of spatial attention.

Overall, the studies presented here further our understanding not only of the interaction between number magnitude, the mental representation of space and the physiology behind the SNARC effect, but also how changes in temporal and spatial attentional processing affect SSVEP amplitude, and whether SSVEP flickering stimuli have an effect on endogenous brain oscillations affecting attentional processing.

GENERAL DISCUSSION

Attending to several and different types of stimuli while performing a task is what we do several times a day, but how we do it is something we are not aware of. However, our brain can process and selectively attend to many relevant components in our environment simultaneously. Although our knowledge on how does this happens is quite extensive, there is still a long path to go to understand each of the cognitive and biological components of attentional processing, and how our brain makes them work together. This allows us to know when to prepare our motor response to continue or discontinue driving when we see the traffic light turning from amber to red, as illustrated in the example described in the introduction.

In this thesis, I presented several studies addressing questions regarding the physiological aspects involved in the effects of number processing on the allocation of spatial attention, and implemented a novel technique for analyzing SSVEP recordings for studying temporal attention. In the following paragraphs, I will discuss the evidence obtained from these studies in light of existing knowledge.

Temporal expectations and the SSVEP

The first study presented in this thesis addressed the question about the feasibility of implementing SSVEP for studying temporal attention, more precisely whether temporal expectations are reflected by changes in SSVEP amplitude, given previous reports on attention-modulation effects of SSVEP amplitude (Norcia et al., 2015).

To our knowledge, our study is the first implementation of SSVEP in the context of temporal attention. We have obtained important evidence for the use of the SSVEP to study temporal attention, to further understand the role of temporal expectations in behavioral and perceptual performance. From the behavioral perspective, our study is in accordance with previous reports about the role of exogenous orienting cues in temporal attention, and our results also confirm that, even when there was no temporal cue in the task, the regularity of the intervals still generates automatic temporal expectation that facilitates the perceptual discrimination process (Rohenkohl et al., 2011). However, because this is the first study implementing SSVEP to study temporal attention, our analyses were focused on whether rhythmic intervals induced temporal attention-modulation effects on the SSVEP amplitude. The result leaves open some interesting questions for future studies: Is it possible that the flicker stimulus has an additive effect on the ongoing brain oscillations that can further explain behavioral performance? Is there any physiological overlapping between the temporal expectations induced by the temporal cues and the flicker stimulation that further explain the behavioral performance in conditions when the time interval was constant? Would the use of different flicker frequencies as the ones used in our study reveal additional mechanisms underlying the enhancement of behavioral performance in a temporal task? Therefore, a deeper understanding of the different electrophysiological mechanisms that support the different components involved in a temporal attention task, and that have an effect on behavior, might be facilitated when using the SSVEP technique. Another benefit of extending the use of the SSVEP to study temporal attention could be to investigate whether the interaction between temporal attention with non-spatial features would enhance behavioral and perceptual performance, in a way similar to what has been reported when combining temporal and spatial attention (Doherty et al., 2005). Moreover, the implementation of SSVEP to study temporal attention, as proposed in this thesis, could extend our knowledge regarding the clinical aspects of timing deficits and how they interact with spatial deficits (Walsh, 2003) that affect behavioral performance as reported in some clinical studies (e.g., Basso, Nichelli, Frassinetti, & Di Pellegrino, 1996). Additionally, because attentional processing is a highly flexible and dynamic aspect of cognition, capable of organizing complex information regulated by the temporal dimension, as it allows the processing of different stimuli periodically (VanRullen, Carlson, & Cavanagh, 2007), the SSVEP technique may constitute an appropriate tool to better understand the time course of temporal expectations as reported in this thesis.

Furthermore, using SSVEP in the context of temporal attention will help to explain some of the physiological components, present in temporal attention, to better understand the mechanisms underlying temporal expectations, and to understand these mechanisms in the context of the neuroscience of attentional processing. For example, in my task I used 6 Hz, 10 Hz and 15 Hz flicker frequencies. The motivation for 6 and 15 Hz was to evaluate whether these two frequencies would show an attention modulation effect on the SSVEP amplitude, and these frequencies were also used partially as control conditions for the alpha flicker. But the most relevant aspect was the selection of the 10 Hz alpha band frequency. We use the alpha band because it seems to be part of the substrate of temporal attention (Busch & VanRullen, 2010; Mathewson et al., 2012), therefore, we suspected that it could be affected in my task, as reported before (Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998), as it could reveal the role of temporal expectations.

It has been suggested that pre-stimulus alpha band activity may exhibit steady states or transient changes in activity. Extending the usability of SSVEP to study temporal expectations might provide a better understanding about: a) the steady states or the transient changes of pre-stimulus alpha as a result of the temporal expectation induced by the task; b) the effects of flicker stimulation on endogenous brain oscillations (Gulbinaite et al., 2017), and c) to properly evaluate the effects of this entrainment on performance. Particularly, implementing the SSVEP to study temporal attention could provide further evidence about the underlying mechanisms of alpha rhythms when induced in response to sine-modulated visual stimulation; also, we may obtain further information about the enhancement of time-locked alpha response upon photic stimulation; and we may better understand the specific mechanisms of alpha frequency band stimulation that affects processing of stimuli when presented with constant interstimulus intervals (Başar, 1998; Ergenoglu et al., 2004).

Besides providing further evidence about the role of the alpha band in temporal attention, and its effect on perceptual processing, the use of SSVEP in temporal attention will help to extend the current knowledge about the different aspects of power and phase of the oscillatory components involved in stimulus processing using constant interstimulus intervals, as previously reported in some ERP studies (Barry, De Pascalis, Hodder, Clarke, & Johnstone, 2003; Ergenoglu et al., 2004).

The results obtained from our task where we combined temporal expectations with the SSVEP also leaves open some questions about the possible interaction between endogenous brain oscillations and flicker stimulation, beyond the entrainment induced by the regularity of the constant interstimulus interval. Mathewson, Gratton, Fabiani, Beck, & Ro (2009) proposed that entrainment of oscillatory brain activity with visual stimulation would induce an effect on endogenous alpha that will resemble the inhibitory process in sensory areas that inhibit the processing of stimuli. Although we expected some overlapping effects between the alpha band frequency flicker and endogenous alpha oscillations, we were not able to disentangle such differences. This is mostly because in our study we wanted to evaluate whether attention modulation effects while performing a temporal attention task could be observed, and the design of the task needs some improvements to allow further analysis of all the physiological aspects involved in an SSVEP-temporal attention study. Another aspect we could not properly evaluate was the coupling of phase and time of the internal oscillators with those involved in the task (Large & Jones, 1999). It will be important for our knowledge of attentional processing to properly describe: 1) whether the constant interstimulus interval that induces temporal expectations also led to increased phase-locking in our task; 2) whether the effect different for a variable ISI; 3) what is the effect of the task-irrelevant flickering in the ongoing brain oscillations; and 4) whether the interaction of all the rhythmic stimuli involved would favor optimal processing when targets are presented at predictable times (Mathewson et al., 2012) or if the effects on the SSVEP do not correlate with the temporal expectancies at all?

Overall, in this thesis we presented for the first time the use of the SSVEP to study temporal attention and our results provide evidence for the feasibility of such an approach to better understand the physiological mechanisms involved in temporal attention. Our findings emphasize the importance of studying temporal attention combined with SSVEP to extend our knowledge about the physiology of temporal attention, its endogenous and exogenous components as well as to understand the deficits in temporal predictability for future clinical populations. For instance, by using SSVEP to study temporal expectations we could better distinguish the different effects of temporal expectations from other aspects of attention during cueing tasks in clinical disorders and older adults.

Effect of mental representation of numbers in spatial attention and SSVEP

In this thesis, I presented the results of two studies conducted to test the hypothesis that passively observing numbers, even if they are not relevant for the task, will induce an automatic shift of spatial attention. Nonetheless, the overall results obtained from both studies are not entirely conclusive. Whether numbers have an active effect on allocating spatial attention by their mere observation remains unresolved. However, it has been shown through several studies that numbers and space share a common neuroanatomical substrate (e.g., Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002) and that there is a positive interaction between them when involved in the same task. But, to date, different reports describe different effects of number observation when involved in a task, and no studies have completely uncovered where this interaction takes place, specially when numbers are not relevant for the task. By using selective and spatial attention tasks combined with SSVEP we showed that when numbers are relevant for the task (parity task, **chapter 4**) or not (target detection task, **chapter 5**), the results did not support a straightforward relationship between number magnitude and the allocation of spatial attention when digits are displayed at fixation and used as cues that precede the presentation of targets.

Behaviorally, the results we obtained in the parity judgment task support the mental representation of numbers, as described by the MNL, and reproduce the so-called SNARC effect (Dehaene et al., 1993). On the contrary, the obtained results in the target detection task are inconsistent with the MNL (Moyer & Landauer, 1967; Restle, 1970) representation of numbers as we could not replicate the SNARC effect. This difference between results provides supporting evidence for cognitive models that explain the interaction between numbers and space in terms other than the MNL. In the parity judgment tasks behavioral performance replicated previous studies supporting the MNL and the SRC (Fitts & Seeger, 1953) models, while the results of the target detection task are more ambiguous. The results obtained from conditions with large magnitude numbers preceding targets on the right visual field are consistent with the MNL and SRC models, but this was not the case for conditions with small numbers preceding targets on the left visual field. Because a general deployment of attention towards the right visual hemifield was observed and a possible effect induced by the spatial salience of the response was observed, we interpreted this as more consistent with the theory of compatibility (Proctor & Cho, 2006). Nonetheless, it is important to note that it is possible that the constant interstimulus interval we used in our task may have affected performance of our participants. Indeed, it has been proposed that there is an interaction between time, space and quantity (Walsh, 2003). According to the Theory of Magnitude (ATOM; Walsh, 2003) there is a related mechanism in the processing of these three dimensions that enhances the processing of information coming from the external world that could regulate the effects of information processing of the spatial and temporal components of our current goal. Since we did not specifically control these parameters in our task that would provide further evidence either at behavioral or physiological level, future studies are needed to properly describe the interaction between numbers, time and spatial attention.

Two last important aspects to possibly explain the difference in results between tasks should be considered. First, the target detection task was a covert attention task where participants had to keep their gaze at fixation point while detecting peripheral targets. We did control horizontal eye movements but we did not control saccadic eye movements and it has been shown that magnitude perception is modulated during saccadic movements (e.g., Binda, Morrone, & Bremmer, 2012). Thus, although participants were informed that numbers were irrelevant for the task, it is possible that between the observation of numbers and the presentation of targets the magnitude of the numbers was activated. Second, it has been proposed that the effects on allocation of spatial attention depend on the relevance and function of the numbers in the task (Abrahamse, Van Dijck, & Fias, 2016; van Dijck et al., 2014), therefore, it is possible that participants kept numbers in their working memory due to the constant observation of numbers during the task. Further Implementation of the SSVEP in the study of numbers and spatial attention would provide evidence to disentangle aspects like the number-attentional effects derived from the instructions of the task or its context (Galfano et al., 2006; Ristic et al., 2006).

On the other hand, in both the parity and target detection tasks we manipulated the task parameters to obtain two different conditions: congruent and incongruent. Cognitive changes produced by the incongruent conditions generate competing responses between the spatial representation of the number and the response hand. Manipulating response conditions in this way may induce cognitive processes like conflict detection, action selection, and selective suppression forcing the selection of only one response from many available ones and has been named response conflict (Cohen & Donner, 2013). These processes are part of cognitive control serving to adapt our behavior according to conflict situations (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). Implementing the SSVEP to study the role of numbers in the allocation of spatial attention would provide further information to better understand the neural mechanisms for the interference of the MNL with action control (Calabria & Rossetti, 2005) and conflict responses (Gut et al., 2012) while resolving spatial attention tasks involving numbers.

We provided evidence for the feasibility of SSVEP to study the effects of number observation in allocating spatial attention. Extending the use of the SSVEP in the context of numerosity would help us to unravel the complex interactions between the what (e.g., numbers) and where (e.g., spatial attention), as well as their timing: how fast (e.g., flickering interference), and for how long (e.g., entrainment of oscillatory brain activity). The implementation of SSVEP could also provide further information about the nature of the brain's representations of numbers useful for clinical populations, when patients are, for example, able to classify numbers as odd or even, but are not able to perform calculations (Fischer, 2001).

In conclusion, our brain is a highly efficient and complex organism that requires the involvement of different networks to perform different processes in parallel. In this thesis, I provided evidence to further understand some of the mechanisms underlying (cognitive and physiological) selective spatial attention. Although the results are not conclusive, one cannot completely deny the attentional effects that numbers could have on spatial attention. We observed some transient effects that can be associated with the covert observation of numbers in our task and that reflect the capacity of the brain to select between multiple features and locations, synchronizing its performance according to the attentional rhythms induced by the context (Dugué, Roberts, & Carrasco, 2016; Jia et al., 2017).

The SSVEP has shown to be a very useful tool to study human cognition although its biological components remain unclear (Norcia et al., 2015). Future studies implementing the SSVEP in the context of temporal expectations and numerosity will provide further evidence about the neural mechanisms underlying SSVEP in these specific types of attentional processing. Our results provide important evidence for the use of the SSVEP under the experimental conditions describe here; however, our results are not strong enough to confirm whether the flickering frequencies used in our experiments did interact (Spaak et al., 2014) or not (Keitel, Quigley, & Ruhnau, 2014) with the ongoing endogenous brain rhythms to influence behavioral performance.

Additionally, a better understanding of the different mechanisms underlying SSVEP in the particular contexts described here will help to disentangle the effects of temporal (e.g., rhythmic intervals) and spatial (e.g., numbers) cueing and their interaction from the effects of neural entrainment induced by the SSVEP. Understanding these individual effects as well as how they interact while performing attentional tasks will provide alternatives to improve SSVEP-based BCI systems (e.g., stimuli presentation in the user interface – see Chapter 2).

Finally, the implementation of the RESS method to analyze SSVEP responses as described in this thesis seems to be an alternative to overcome the limitations coming from the short recording intervals used in SSVEP-based BCI systems (see Chapter 2). Given the restrictions in the efficiency of signal processing and decoding algorithms implemented to extract SSVEP components in SSVEP-based BCI systems, the RESS method provides an efficient alternative to extract different SSVEP frequency components and their harmonics as compared with other methods currently use to analyze SSVEP-based BCI systems. Additionally, implementing the RESS to analyze SSVEP-based BCI systems may reduce erroneous detections that are quite likely to occur in traditional SSVEP-based BCI systems (Mora-Cortes et al., 2014 – see Chapter 2).

Methodological considerations

We have provided important evidence for the use of SSVEP to study temporal attention. However, in order to extend the implementation of the SSVEP technique to the field of temporal attention, we recommend introducing some modifications in the design of the task and to optimize the experimental parameters for SSVEP use.

Selection of flicker stimulation: our results showed temporal attention effects in the constant conditions for the 10 Hz and its second harmonic at 20 Hz, for the fundamental frequency at 6 Hz, and the second harmonic of the 15 Hz flicker, 30 Hz, as expected. However, inverse effects were observed for the fundamental frequency at 15 Hz and the second harmonic of the 6Hz flicker, 12 Hz. Therefore, we can confirm the use of the alpha-band flicker as part of the SSVEP stimulation, but using flicker stimuli out of the alpha band range may provide more clear-cut results, for example between 20 and 30 Hz (Müller, Picton, et al., 1998; Regan, 1989).

Target onset phase-locking: In our task, target presentation was not phase-locked with respect to flicker stimulus onset. Thus, adjusting this parameter will provide additional insights about more useful implementation of SSVEP in the context of temporal attention.

Flicker position: In our task the flicker stimuli were presented peripherally which was uncomfortable for some participants. Presenting the stimuli foveally will result in a less uncomfortable task for participants and will provide better measurements of the attention effect (Walter et al., 2012).

Although our results about the SNARC effect and spatial attention provided important evidence, here I summarize some methodological considerations for future studies using the SSVEP to study the interaction between number processing and spatial attention.

Counterbalancing the hand response: although it has been shown that handedness does not affect performance in parity judgment tasks (Gut et al., 2012), counterbalancing hand mapping would provide a wider frame about the changes in performance (if any) within subjects while performing the same task. Therefore, this aspect should be considered in future SSVEP-parity task studies.

Number of numbers: if we assume the mental representation of numbers in the target detection task according to PCT, given the fact that we use eight different digits (1,2,3,4,6,7,8,9), numerical cues could affect the cognitive performance in the task because it is possible that participants had to define the distance between each number cue with respect to the center of the mental reference representation to maintain numbers around this center on every trial. Particularly because in most of the SNARC reports only four digits (1, 2 vs. 8,9) have been used.

Role of number magnitude: future studies should probably include a control experiment to test whether the evaluation of number magnitude used as central cue before target presentation would reflect a SNARC-spatial attention effect (e.g., Zanolie & Pecher, 2014, Exp 3), and to test how judgment of magnitude affects the SSVEP amplitude, to provide more reliable numerical effect on spatial attention, in both a unimanual and bimanual response task.

Time, space and quantity, the missing interactions to better understand attentional processing?

The results presented in this thesis have shed light on the effect of temporal attention and number representation on SSVEP amplitude, and in this way provide important evidence for the implementation of SSVEP to study the effects of time, numbers, and space, and how they interact to determine our performance. However, these studies focused either on one aspect (e.g., time) or the other (e.g., numbers) but not on the direct interaction between them. Thus, to better understand each of these components individually and how they interact to enhance our performance, future SSVEP studies should be designed to control for these aspects. Time, numbers, and space imply abstract definitions that share one similar semantic concept: numbers. Therefore, a relationship between them is to be expected (Bonato et al., 2012; Burr, Ross, Binda, & Morrone, 2011; Cheal & Lyon, 1991; Walsh, 2003)

CONCLUSION

In this thesis I presented important evidence for the implementation of SSVEP to study temporal attention. Temporal attention-modulation effects were observe for flickering stimuli in the alpha-band frequency for the fundamental and the second harmonic, supporting the hypothesis that alpha is part of the neurophysiological substrate of temporal attention. And the studies about SNARC effect and its role in spatial attention provided physiological evidence for the effect of numbers in spatial attention when they are part of the task, and inconclusive evidence was obtained for the role of numbers in spatial attention when they are not relevant for the task. Extending the use of SSVEP as has been shown in this thesis will provide further evidence to elucidate the specific mechanisms involved in entrainment of ongoing oscillations induced by different external sources (e.g., rhythmic stimuli and rhythmic time intervals) with the internal rhythms (e.g. endogenous attention), to have a more comprehensive understating of this interaction and its effects on behavior, while waiting for the traffic light to turn from red to green for example.

Dutch summary
(Nederlandse samenvatting)

SAMENVATTING

Dagelijkse activiteiten vereisen dat onze hersenen selectief aandacht besteden aan aspecten van de omgeving die het meest relevant zijn om ons gedrag te sturen en te monitoren, en dat ongewenste uitkomsten van onze en andermans handelingen worden voorkomen. Omdat het prioriteren en verwerken van relevante informatie zeer veeleisend kan zijn, en dus moeilijk is om te allen tijde vol te houden, moeten onze hersenen verschillende omgevingseigenschappen correct selecteren en filteren (bijvoorbeeld op basis van locatie, fysieke kenmerken zoals kleur of vorm, of tijdstip van optreden) en ons cognitieve controlesysteem aanpassen, onder andere, zodat ons gedrag in overeenkomst is met de vereisten van elke specifieke situatie.

Één van de doelen van de cognitieve neurowetenschappen is om te begrijpen hoe onze hersenen informatie selecteren en verwerken om een juiste respons te genereren. Hiertoe zijn verschillende technieken geïmplementeerd voor het bestuderen van cognitieve processen, zoals aandachtsprocessen, cognitieve controle en temporele voorspelbaarheid, waaronder gedragstesten en niet-invasieve elektrofysiologische opnames. Omdat cognitieve verwerking snel kan worden ingezet en veranderen (binnen een fractie van een seconde), zijn hersenbeeldvormingstechnieken met hoge temporele resolutie bijzonder nuttig voor het bestuderen van de bovengenoemde cognitieve processen. Elektro-encefalografie (EEG), met een temporele resolutie in de orde van milliseconden, is een van de meest gebruikte beeldvormingstechnieken voor het bestuderen van menselijke cognitie, waarbinnen de *steady-state visual evoked potential* (SSVEP) een veelgebruikte techniek is.

Bij de SSVEP-techniek worden herhaaldelijk flikkerende visuele stimuli gebruikt, en wordt de EEG-respons die deze stimuli opwekken gemeten op de hoofdhuid. Terwijl de visuele stimulus flikkert (zoals een flitslicht), resoneert de activiteit van grote groepen hersencellen in de vroege visuele verwerkingsgebieden van de hersenen mee met dezelfde temporele frequentie, hetgeen leidt tot een sinusvormige EEG-respons: de SSVEP (Regan, 1989). De SSVEP is uitgebreid gebruikt om visuele aandacht te bestuderen, omdat de amplitude ervan correleert met de hoeveelheid aandacht die aan de flikkerende stimulus wordt besteed. Hoewel veranderingen in de SSVEP-amplitude in algemene zin gerelateerd zijn aan de effecten van aandacht, suggereerden Ding et al. (2006) dat de aandachtsmodulatie afhankelijk kan zijn van de stimulatiefrequentie, en dat voor frequenties in de lagere alfaband (8–10 Hz) een toename in SSVEP-amplitude kan worden gevonden als de flikkeringsfrequentie perifeer is ten opzichte van het de geattendeerde stimulus.

In dit proefschrift rapporteer ik over het gebruik van de SSVEP om temporele aandacht en de relatie tussen ruimtelijke aandacht en mentale representatie van getallen te bestuderen.

Ten eerste, omdat het begrijpen van de cognitieve en biologische aspecten van cognitie in zowel gezonde als klinische populaties onze kennis over dergelijke processen zou vergroten, en om te helpen bij de ontwikkeling van oplossingen die klinische populaties ten goede zouden komen, heb ik in **hoofdstuk 2** een uitgebreide review van *Brain-Computer Interfaces* (BCIs) gepresenteerd. BCI-systemen stellen een gebruiker in staat te communiceren met de buitenwereld door zijn/haar hersenactiviteit direct in (computer) commando's te vertalen, waardoor de reguliere motorische aansturing omzeilt kan worden. De review wordt gepresenteerd in de context van taalmodelapplicaties die niet-invasieve BCI-gebaseerde communicatiesystemen aanvullen. De review biedt een overzicht van de voordelen en uitdagingen bij het implementeren van taalmodellen in combinatie met verschillende technieken, waaronder het gebruik van de SSVEP, in BCI-gebaseerde communicatiesystemen in combinatie met andere *Ambient Assisted Living* (AAL) -technologieën.

Voor zover ik heb kunnen nagaan, is de SSVEP-methode niet eerder gebruikt om temporele aandacht te bestuderen. Dit is belangrijk omdat is aangetoond dat temporele voorspelbaarheid aandacht en sensorische verwerking in verschillende domeinen verbetert (Woodrow, 1914). Het is belangrijk om te demonstreren dat de SSVEP relevant is voor het bestuderen van temporele aandacht, om fundamentele wetenschappelijke redenen maar ook voor toekomstige diagnostiek, omdat temporele aandacht en het juiste gebruik van temporele *cues* om gedrag te sturen verminderd zijn in verschillende klinische aandoeningen, waaronder de ziekte van Parkinson (Rochester et al., 2005) en schizofrenie (Silberstein et al., 2000). In het onderzoekslab wordt temporele aandacht vaak bestudeerd als aandacht voor het moment dat een bepaalde stimulus verschijnt of van het scherm verdwijnt (Babiloni et al., 2004). Verscheidene onderzoeken hebben ERPs (bijv. Miniussi, Wilding, Coull, & Nobre, 1999) of neurale oscillaties (bijv. Klimesch, 2012) gemeten om temporele aandacht te bestuderen. Neurale oscillaties in de alfaband (~10 Hz) lijken onderdeel te zijn van het substraat van temporele aandacht. Één van de theorieën over temporele aandacht suggereert het bestaan van interne oscillatoren waarvan de aandachtspulsen kunnen worden gelijkgeschakeld met de omgevingsritmiek, om het verwerken van stimuli te verbeteren op voorspelbare tijdstippen (Mathewson, Fabiani, Monica, et al., 2010). Temporele verwachtingen houden dan gelijke tred met de fase van lopende hersenoscillaties, zodat doelherkenning verbeterd wanneer tijdsintervallen voorspelbaar zijn (Schroeder & Lakatos, 2010).

We hebben een eerste experiment ontworpen om te evalueren of SSVEP-stimulatie en de temporele dynamiek daarvan kunnen worden gebruikt om temporele aandacht te bestuderen, en om te evalueren of aandachtsmodulatie van SSVEPs vergelijkbaar is voor drie verschillende frequenties (**hoofdstuk 3**). Omdat temporele verwachtingen het mogelijk maken dat maximale doelherkenning op voorspelbare tijdstippen een effect op de respons van de deelnemer heeft, hebben we het inter-stimulusinterval (ISI; constant versus variabel) gemanipuleerd om te evalueren of er een effect is van SSVEP-stimulatie op gedrag. De verkregen gedragsresultaten repliceerden eerdere onderzoeken die de voordelen bevestigen van temporele verwachtingen ten aanzien van taakprestatie bij een constante ISI. EEG-analyses onthulden robuuste SSVEP-amplitudes voor alle flikkerfrequenties, hoewel een hoofdeffect van temporele verwachtingen op de SSVEP-amplitude niet significant was. Aanvullende analyses onthulden temporele voorspelbaarheid-gerelateerde modulaties van SSVEP-amplitude bij 10 Hz en de tweede harmonische (20 Hz), en voor de 6 Hz flikkering, maar niet voor 15 Hz, voor alle ISI-condities. Deze resultaten leveren enig bewijs dat de SSVEP-techniek het mogelijk maakt om temporele aandacht voor stimuli te bestuderen met flikkerfrequenties rond de alfaband.

Een andere belangrijke component van aandacht is het vermogen om de aandacht in het visuele veld te richten op een bepaalde stimulus, en tegelijkertijd de verwerking van concurrerende stimuli op andere locaties te onderdrukken: de zogeheten ruimtelijke aandacht. De representatie van getallen in de hersenen is ruimtelijk georganiseerd, op de zogeheten mentale getallenlijn. Het *Spatial-Numerical Association of Responses Codes* (SNARC) effect beschrijft de relatie tussen de ruimtelijke representatie van getallen in de hersenen en de getalsgrootte (S Dehaene et al., 1993). Het SNARC-effect is gebruikt om de reactietijden van deelnemers bij een pariteitsbeoordelingstaak te verklaren. De grootte van het getal op de mentale getallenlijn leidt tot snellere responsen wanneer de positie van het getal overeenkomt met de responshand. Deze interactie tussen de mentale representatie van getallen en verbetering van prestatie is beschreven in taken waarbij de getalsgrootte relevant is voor de taak (grootte-beoordeling) maar ook wanneer de getalsgrootte niet taakrelevant is (pariteitsbeoordeling; Fias & Fischer, 2004; Fias, Lauwereyns, & Lammertyn, 2001).

De studies over ruimtelijke aandacht en mentale representatie van getallen die gerapporteerd worden in dit proefschrift betreffen aangepaste versies van de SNARC-taak. Het doel was om de SSVEP-techniek te gebruiken om direct bewijs (of gebrek daaraan) te demonstreren voor de hypothese dat SNARC ruimtelijke verschuivingen van aandacht induceert. Dit is een nieuwe benadering voor het bestuderen van getalsverwerking en het effect ervan op de verdeling van ruimtelijke aandacht. Eerdere EEG-onderzoeken naar spatiale aandacht tijdens *coverte* aandachtsverschuivingen hebben bewijs geleverd voor veranderingen in SSVEP-amplitude op posterieure en contralaterale locaties voor detectie van geattendeerde stimuli, vergeleken met niet-geattendeerde flikkerende stimuli (M. M. Müller & Hillyard, 2000). Omdat aandachtsverschuivingen kunnen worden bereikt zonder de ogen te bewegen—*coverte* aandacht, waarbij de deelnemers hun blik op het fixatiepunt houden terwijl de stimulus links of rechts van het fixatiepunt wordt weergegeven—hebben we een aangepaste versie van de taak van Fischer *et al.* (2003) geïmplementeerd. In een coverte ruimtelijke aandachtstaak worden deelnemers gevraagd om het midden van het scherm te fixeren terwijl ze een stimulus detecteren die links of rechts van het fixatiepunt wordt weergegeven. Op elke *trial*, vóór de presentatie van de stimulus, werd één van vier cijfers weergegeven. De deelnemers kregen te horen dat de cijfers niet relevant waren voor de taak.

De resultaten van deze pariteitsbeoordelingstaak (classificeer getallen als oneven of even, onafhankelijk van de grootte van de getallen), beschreven in **hoofdstuk 4**, repliceerden de verwachte gedragspatronen voorspeld door het SNARC-effect. We hebben ook significante veranderingen in de SSVEP-amplitude waargenomen (in vergelijking met de *baseline*) voor de linker en rechter flikkerende stimuli, voor zowel de congruente als de incongruente condities. Statistisch significante verschillen tussen de congruente en incongruente condities waren groter voor de congruente conditie voor de flikkerende stimulus aan de linkerkant. Samenvattend ondersteunen deze bevindingen de hypothese dat, als getallen deel uitmaken van de taak, maar hun grootte niet relevant is, het SNARC ruimtelijke aandachtseffect wordt opgewekt als een cognitief effect, dat voortkomt uit de mentale representatie van getallen en de relatie ervan met de ruimtelijke representatie, meer dan alleen een motoreffect. Resultaten van de stimulusdetectietaak (detectie van perifeer gepresenteerde stimuli terwijl getallen die niet relevant waren voor de taak genegeerd dienen te worden) in **hoofdstuk 5** toonden voordelen voor de interactie tussen grote getallen voorafgaand aan stimuli die in het rechter hemiveld gepresenteerd werden, waarmee het SNARC gedragseffect gedeeltelijk gerepliceerd werd. Daarnaast toonden EEG SSVEP-resultaten een aandachtsmodulatie-effect voor het verschil tussen congruente en incongruente condities aan, waarbij grotere SSVEP-amplituden voorkwamen in de incongruente conditie (kleine getallen, stimuli aan de rechterkant) voor de flikkerende stimuli in het linker hemiveld, en in de congruente conditie (grote getallen, stimuli aan de rechterkant) voor de flikkerende stimuli in het rechter hemiveld. Onze resultaten tonen aan dat het passief observeren van getallen geen automatische verschuiving van ruimtelijke aandacht veroorzaakt, of op zijn minst niet een effect dat elektrofysiologisch gemeten zou kunnen worden. Ze tonen ook aan dat, zelfs als getallen niet relevant zijn voor de taak, de semantische representatie van getallen geactiveerd wordt.

Samen bieden de resultaten in dit proefschrift ondersteunend bewijs voor taalmodellen binnen BCI-systemen, aangezien een significante verbetering van de spellingsprestaties kan worden bereikt, wat nieuwe mogelijkheden biedt voor BCI-integratie in de AAL-gemeenschap en voor rehabilitatie. Anderzijds dragen de hier gerapporteerde resultaten bij aan een beter begrip van de psychofysiologische componenten van temporele en ruimtelijke aandachtsprocessen, de relatie tussen flikkerende frequenties en endogene hersenoscillaties, en de relatie van deze endogene hersenoscillaties met informatieverwerking, cognitieve controle en gedrag. Bovendien, voor alle studies die in dit proefschrift gepresenteerd worden, lever ik belangrijk bewijs voor een toekomstige implementatie van de SSVEP-techniek om temporele aandacht te bestuderen, alsmede de rol van door getallen geïnduceerde automatische verschuivingen van ruimtelijke aandacht.

Over het algemeen bevorderen de hier gepresenteerde onderzoeken ons inzicht in niet alleen de interactie tussen getalsgrootte, de mentale representatie van ruimte en de fysiologie achter het SNARC-effect, maar ook hoe veranderingen in temporele en ruimtelijke aandachtsprocessen de SSVEP-amplitude beïnvloeden, en of SSVEP-flikkerende stimuli een effect hebben op endogene hersenoscillaties die de aandachtprocessen beïnvloeden.

REFERENCES

Abrahamse, E., Van Dijck, J. P., & Fias, W. (2016). How does working memory enable number-induced spatial biases? *Frontiers in Psychology*, *7*(JUN), 1–11. http://doi.org/10.3389/fpsyg.2016.00977

Abrams, J., Barbot, A., & Carrasco, M. (2010). Voluntary attention increases perceived spatial frequency. *Attention, Perception, & Psychophysics*, *72*(6), 1510–1521. http://doi.org/10.3758/APP.72.6.1510

Acqualagna, L., & Blankertz, B. (2013). Gaze-independent BCI-spelling using rapid serial visual presentation (RSVP). *Clinical Neurophysiology*, *124*(5), 901–908. http://doi.org/10.1016/j.clinph.2012.12.050

Acqualagna, L., Treder, M. S., Schreuder, M., & Blankertz, B. (2010). A novel Brain-Computer Interface based on the rapid serial visual presentation paradigm. In *Annual International Conference of the IEEE EMBS* (pp. 2686–2689). Buenos Aires, Argentina: IEEE. http://doi.org/10.1109/IEMBS.2010.5626548

Ahi, S. T., Kambara, H., & Koike, Y. (2011). A dictionary-driven P300 speller with a modified interface. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *19*(1), 6–14. http://doi.org/10.1109/TNSRE.2010.2049373

Akkal, D., Escola, L., Bioulac, B., & Burbaud, P. (2004). Time predictability modulates pre-supplementary motor area neuronal activity. *NeuroReport*, *15*(8), 1283–1286. http://doi.org/10.1097/01.wnr.0000127347.87552.87

Akram, F., Metwally, M. K., Han, H. S., Jeon, H. J., & Kim, T. S. (2013). A novel P300-based BCI system for words typing. In *2013 International Winter Workshop on Brain-Computer Interface, BCI 2013* (pp. 24–25). Jeongsun-kun, Gangwon province, South Korea: IEEE. http://doi.org/10.1109/IWW-BCI.2013.6506617

Ales, J., Farzin, F., Rossion, B., & Norcia, A. M. (2012). An objective method for measuring face detection thresholds using the sweep steady-state visual evoked response. *Journal of Vision*, *12*(2012), 1–18. http://doi.org/10.1167/12.10.18.

Allison, B. Z., & Pineda, J. A. (2003). ERPs Evoked by different matrix sizes: Implications for a Brain Computer Interface (BCI) system. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *11*(2), 110–113. http://doi.org/10.1109/TNSRE.2003.814448

Allison, B. Z., Wolpaw, E. W., & Wolpaw, J. R. (2007). Brain-Computer Interface systems: Progress and prospects. *Expert Review of Medical Devices*, *4*(4), 463–474. http://doi.org/10.1586/17434440.4.4.463

Andersen, S. K., & Müller, M. M. (2010). Behavioral performance follows the time course of neural facilitation and suppression during cued shifts of feature-selective attention. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(31), 13878–82. http://doi.org/10.1073/pnas.1002436107

Andersen, S. K., Müller, M. M., & Hillyard, S. A. (2009). Color-selective attention need not be mediated by spatial attention. *Journal of Vision*, *9*(6), 2.1-7. http://doi.org/10.1167/9.6.2

Andres, M., Ostry, D. J., Nicol, F., & Paus, T. (2008). Time course of number magnitude interference during grasping. *Cortex*, *44*(4), 414–419. http://doi.org/10.1016/j.cortex.2007.08.007

Ang, K. K., Chin, Z. Y., Zhang, H., & Guan, C. (2008). Filter Bank Common Spatial Pattern (FBCSP) in Brain-Computer Interface. In *2008 IEEE International Joint Conference on Neural Networks (IEEE World Congress on Computational Intelligence)* (pp. 2390–2397). Hong Kong, China. http://doi.org/10.1109/IJCNN.2008.4634130

Angel, P. G., Bojorges-Valdez, E., & Yanez-Suarez, O. (2011). SSVEP-based BCI control of the DASHER writing system. In *2011 5th International IEEE/EMBS Conference on Neural Engineering* (pp. 446–448). Cancun, Mexico: Ieee. http://doi.org/10.1109/NER.2011.5910582
Arend, I., Ashkenazi, S., Yuen, K., Ofir, S., & Henik, A. (2017). Automatic numerical-spatial association in synaesthesia: An fMRI investigation. *Neuropsychologia*, *95*(September 2016), 259–266. http://doi.org/10.1016/j.neuropsychologia.2016.12.023
Aricò, P., Aloise, F., Schettini, F., Riccio, A., Salinari, S., Babiloni, F., … Cincotti, F. (2011). GeoSpell: An alternative P300-based speller interface towards no eye gaze required. *International Journal of Bioelectromagnetism*, *13*(3), 152–153.
Babiloni, C., Miniussi, C., Babiloni, F., Carducci, F., Cincotti, F., Del Percio, C., … Rossini, P. M. (2004). Sub-second "temporal attention" modulates alpha rhythms. A high-resolution EEG study. *Cognitive Brain Research*, *19*(3), 259–268. http://doi.org/10.1016/j.cogbrainres.2003.12.010
Barbot, A., Landy, M. S., & Carrasco, M. (2011). Exogenous attention enhances 2nd-order contrast sensitivity. *Vision Research*, *51*(9), 1086–1098. http://doi.org/10.1016/j.visres.2011.02.022
Barry, R. J., De Pascalis, V., Hodder, D., Clarke, A. R., & Johnstone, S. J. (2003). Preferred EEG brain states at stimulus onset in a fixed interstimulus interval auditory oddball task, and their effects on ERP components. *International Journal of Psychophysiology*, *47*, 187–198. http://doi.org/10.1016/S0167-8760(02)00151-4
Başar, E. (1998). Oscillatory components of evoked potentials are real brain responses related to function. In *Brain Function and Oscillations*. Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-642-72192-2_19
Bashashati, A., Fatourechi, M., Ward, R. K., & Birch, G. E. (2007). A survey of signal processing algorithms in brain-computer interfaces based on electrical brain signals. *Journal of Neural Engineering*, *4*(2), R32-57. http://doi.org/10.1088/1741-2560/4/2/R03
Basso, G., Nichelli, P., Frassinetti, F., & Di Pellegrino, G. (1996). Time perception in a neglected space. *NeuroReport*. http://doi.org/10.1097/00001756-199609020-00009
Becedas, J. (2012). Brain–Machine Interfaces: Basis and advances. *IEEE Transactions on Systems, Man, and Cybernetics, C Applications and Reviews*, *42*(6), 825–836. http://doi.org/10.1109/TSMCC.2012.2203301
Beker, H., & Piper, F. (1982). *Cipher systems: The Protection of communications*. London, UK: International Thomson Publishing Ltd. http://doi.org/10.1112/blms/15.5.521
Belmonte, M. (1998). Shifts of visual spatial attention modulate a steady-state visual evoked potential. *Cognitive Brain Research*, *6*(4), 295–307. http://doi.org/10.1016/S0926-6410(98)00007-X
Besle, J., Schevon, C. A., Mehta, A. D., Lakatos, P., Goodman, R. R., McKhann, G. M., … Schroeder, C. E. (2011). Tuning of the Human Neocortex to the Temporal Dynamics of Attended Events. *Journal of Neuroscience*, *31*(9), 3176–3185. http://doi.org/10.1523/JNEUROSCI.4518-10.2011
Bin, G., Gao, X., Wang, Y., Hong, B., & Gao, S. (2009). VEP-based Brain-computer Interfaces: Time, frequency, and code modulations. *IEEE Computational Intelligence Magazine*, *4*(4), 22–26. http://doi.org/10.1109/MCI.2009.934562
Bin, G., Gao, X., Wang, Y., Li, Y., Hong, B., & Gao, S. (2011). A high-speed BCI based on code modulation VEP. *Journal of Neural Engineering*, *8*(2), 1–5. http://doi.org/10.1088/1741-2560/8/2/025015
Binda, P., Morrone, M. C., & Bremmer, F. (2012). Saccadic Compression of Symbolic Numerical Magnitude. *PLoS ONE*, *7*(11).

http://doi.org/https://10.1371/journal.pone.0049587
Birbaumer, N., & Cohen, L. G. (2007). Brain-computer interfaces: Communication and restoration of movement in paralysis. *The Journal of Physiology*, *579*(Pt 3), 621–36. http://doi.org/10.1113/jphysiol.2006.125633
Blankertz, B., Dornhege, G., Krauledat, M., Müller, K.-R., & Curio, G. (2007). The non-invasive Berlin Brain-Computer Interface: Fast acquisition of effective performance in untrained subjects. *NeuroImage*, *37*(2), 539–50. http://doi.org/10.1016/j.neuroimage.2007.01.051
Blankertz, B., Dornhege, G., Krauledat, M., Schroeder, M., Williamson, J., Murray-Smith, R., & Müller, K.-R. (2006). The Berlin Brain-Computer Interface presents the novel mental typewriter Hex-o-Spell. *3rd International BCI Workshop and Training Course, Graz, 2006, Graz, Austria(2006).*, 2–3. http://doi.org/10.1.1.66.7603
Blaser, E., Sperling, G., & Lu, Z.-L. (1999). Measuring the amplification of attention. *Proceedings of the National Academy of Sciences*, *96*(20), 11681–11686. http://doi.org/10.1073/pnas.96.20.11681
Bonato, M., Priftis, K., Marenzi, R., & Zorzi, M. (2009). Normal and Impaired Reflexive Orienting of Attention after Central Nonpredictive Cues. *Journal of Cognitive Neuroscience*, *21*(4), 745–759. http://doi.org/10.1162/jocn.2009.21054
Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: Evidence for a mental time line. *Neuroscience and Biobehavioral Reviews*, *36*(10), 2257–2273. http://doi.org/10.1016/j.neubiorev.2012.08.007
Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*(4), 433–436. http://doi.org/10.1163/156856897X00357
Bridwell, D. A., & Srinivasan, R. (2012). Distinct attention networks for feature enhancement and suppression in vision. *Psychological Science*, *23*(10), 1151–1158. http://doi.org/10.1177/0956797612440099
Brouwer, A. M., & van Erp, J. B. F. (2010). A tactile P300 Brain-Computer Interface. *Frontiers in Neuroscience*, *4*(MAY), 1–11. http://doi.org/10.3389/fnins.2010.00019
Brunner, P., Bianchi, L., Guger, C., Cincotti, F., & Schalk, G. (2011). Current trends in hardware and software for brain-computer interfaces (BCIs). *Journal of Neural Engineering*, *8*(2), 1–7. http://doi.org/10.1088/1741-2560/8/2/025001
Bruyer, R., & Brysbaert, M. (2011). Combining Speed and Accuracy in Cognitive. *Psychologica Belgica*, *51*, 5–13. http://doi.org/10.5334/pb-51-1-5
Bulf, H., Cassia, V. M., & de Hevia, M. D. (2014). Are numbers, size and brightness equally efficient in orienting visual attention? Evidence from an eye-tracking study. *PLoS ONE*, *9*(6). http://doi.org/10.1371/journal.pone.0099499
Bundesen, C. (1990). A theory of visual attention. *Psychol Rev*, *97*(4), 523–547. http://doi.org/10.1037/0033-295X.97.4.523
Burr, D. C., Ross, J., Binda, P., & Morrone, M. C. (2011). Saccades Compress Space, Time, and Number. *Space, Time and Number in the Brain*, *14*(12), 175–186. http://doi.org/10.1016/B978-0-12-385948-8.00012-8
Busch, N., & VanRullen, R. (2010). Spontaneous EEG oscillations reveal periodic sampling of visual attention. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(37), 16048–53. http://doi.org/10.1073/pnas.1004801107
Calabria, M., & Rossetti, Y. (2005). Interference between number processing and line bisection: A methodology. *Neuropsychologia*, *43*(5), 779–783. http://doi.org/10.1016/j.neuropsychologia.2004.06.027
Carrasco, M., & Yeshurun, Y. (1998). The contribution of covert attention to the set-size and eccentricity effects in visual search. *Journal of Experimental Psychology. Human Perception and Performance*, *24*(2), 673–692. http://doi.org/10.1037/0096-

1523.24.2.673
Casarotti, M., Michielin, M., Zorzi, M., & Umiltà, C. (2007). Temporal order judgment reveals how number magnitude affects visuospatial attention. *Cognition*, *102*(1), 101–117. http://doi.org/10.1016/j.cognition.2006.09.001
Castiello, U., & Umiltà, C. (1992). Splitting focal attention. *Journal of Experimental Psychology : Human Perception and Performance*, *18*(3), 837–848. http://doi.org/10.1037/0096-1523.18.3.837
Cattaneo, Z., Silvanto, J., Battelli, L., & Pascual-leone, A. (2009). The mental number line modulates visual cortical excitability. *Neuroscience Letters*, *462*(3), 253–256. http://doi.org/10.1016/j.neulet.2009.07.027
Cecotti, H. (2010). Spelling with Brain-Computer Interfaces Current trends and prospects. In *Cinquième conférence plénière française de Neurosciences Computationnelles, (Neurocomp'10)* (pp. 1–6). Lyon, France: Neurocomp. Retrieved from https://hal.archives-ouvertes.fr/hal-00553422
Cecotti, H. (2011). Spelling with non-invasive Brain-Computer Interfaces - current and future trends. *Journal of Physiology Paris*, *105*(1–3), 106–114. http://doi.org/10.1016/j.jphysparis.2011.08.003
Cecotti, H., Sato-Reinhold, J., Sy, J. L., Elliott, J. C., Eckstein, M. P., & Giesbrecht, B. (2011). Impact of target probability on single-trial EEG target detection in a difficult rapid serial visual presentation task. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, 6381–6384. http://doi.org/10.1109/IEMBS.2011.6091575
Cecotti, H., Volosyak, I., & Gräser, A. (2009). Evaluation of an SSVEP based Brain-Computer Interface on the command and application levels. In *4th International IEEE/EMBS Conference on Neural Engineering,* (pp. 474–477). Antalaya, Turkey. http://doi.org/10.1109/NER.2009.5109336
Chatterjee, A., Aggarwal, V., Ramos, A., Acharya, S., & Thakor, N. V. (2007). A Brain-Computer Interface with vibrotactile biofeedback for haptic information. *Journal of NeuroEngineering and Rehabilitation*, *4*, 1–12. http://doi.org/10.1186/1743-0003-4-40
Cheal, M. Lou, & Lyon, D. R. (1991). Central and Peripheral Precuing of Forced-choice Discrimination. *The Quarterly Journal of Experimental Psychology Section A*, *43*(4), 859–880. http://doi.org/10.1080/14640749108400960
Chen, Y., Seth, A. K., Gally, J. A., & Edelman, G. M. (2003). The power of human brain magnetoencephalographic signals can be modulated up or down by changes in an attentive visual task. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(6), 3501–6. http://doi.org/10.1073/pnas.0337630100
Chennu, S., Alsufyani, A., Filetti, M., Owen, A. M., & Bowman, H. (2013). The cost of space independence in P300-BCI spellers. *Journal of NeuroEngineering and Rehabilitation*, *10*(1), 1–13. http://doi.org/10.1186/1743-0003-10-82
Chinello, A., de Hevia, M. D., Geraci, C., & Girelli, L. (2012). Finding the spatial-numerical association of response codes (SNARC) in signed numbers: Notational effects in accessing number representation. *Functional Neurology*, *27*(3), 177–185.
Chochon, F., Cohen, L., Moortele, P. F. van de, Dehaene, S., & Inserm, U. (1999). Differential Contributions of the Left and Right Inferior Parietal Lobules to Number Processing. *Journal of Cognitive Neuroscience*, *11*(6), 617–630. http://doi.org/10.1162/089892999563689
Chumerin, N., Manyakov, N. V., Combaz, A., Suykens, J. A. K., & Van Hulle, M. M. (2009). An application of feature selection to on-line P300 detection in brain-computer interface. *Machine Learning for Signal Processing XIX - Proceedings of the 2009 IEEE Signal*

Processing Society Workshop, MLSP 2009. http://doi.org/10.1109/MLSP.2009.5306244
Chumerin, N., Manyakov, N. V, Combaz, A., Suykens, J. A. K., Yazicioglu, R. F., Torfs, T., … Van Hulle, M. M. (2009). P300 detection based on feature extraction in on-line Brain-Computer Interface. In *Lecture Notes in Computer Science* (Vol. 5803/2009, pp. 339–346). http://doi.org/10.1007/978-3-642-04617-9_43
Chumerin, N., Manyakov, N. V, Vliet, M. Van, Robben, A., Combaz, A., & Van Hulle, M. M. (2013). Steady-State Visual Evoked Potential-based computer gaming on a consumer-grade EEG device. *IEEE Transactions on Computational Intelligence and AI in Games*, *5*(2), 100–110. http://doi.org/10.1109/TCIAIG.2012.2225623
Cohen, M. X. (2014). *Analyzing Neural Time Series: Theory and practice* (First). Cambridge, MA: MIT Press. http://doi.org/10.1017/CBO9781107415324.004
Cohen, M. X. (2017). Comparison of linear spatial filters for identifying oscillatory activity in multichannel data. *Journal of Neuroscience Methods*, *278*, 1–12. http://doi.org/10.1016/j.jneumeth.2016.12.016
Cohen, M. X., & Donner, T. H. (2013). Midfrontal conflict-related theta-band power reflects neural oscillations that predict behavior. *Journal of Neurophysiology*, *110*(12), 2752–63. http://doi.org/10.1152/jn.00479.2013
Cohen, M. X., & Gulbinaite, R. (2017). Rhythmic entrainment source separation: Optimizing analyses of neural responses to rhythmic sensory stimulation. *NeuroImage*, *147*(August 2016), 43–56. http://doi.org/https://dx.doi.org/10.1016/j.neuroimage.2016.11.036
Collinger, J. L., Wodlinger, B., Downey, J. E., Wang, W., Tyler-kabara, E. C., Weber, D. J., … Schwartz, A. B. (2013). High-performance neuroprosthetic control by an individual with tetraplegia. *Lancet*, *381*(9866), 557–564. http://doi.org/10.1016/S0140-6736(12)61816-9
Combaz, A., Chumerin, N., Manyakov, N. V., Robben, A., Suykens, J. A. K., & Van Hulle, M. M. (2012). Towards the detection of error-related potentials and its integration in the context of a P300 speller Brain-Computer Interface. *Neurocomputing*, *80*, 73–82. http://doi.org/10.1016/j.neucom.2011.09.013
Compton, B. J., & Logan, G. D. (1993). Evaluating a computational model of perceptual grouping by proximity. *Perception & Psychophysics*, *53*(4), 403–421. http://doi.org/10.3758/BF03206783
Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 201–215. http://doi.org/10.1038/nrn755
Correa, Á. (2010). Enhancing behavioural performance by visual temporal orienting. In A. C. Nobre & J. T. Coull (Eds.), *Attention and time* (pp. 357–370). Oxford: Oxford University Press.
Correa, Á., Lupiáñez, J., Madrid, E., & Tudela, P. (2006). Temporal attention enhances early visual processing: A review and new evidence from event-related potentials. *Brain Research*, *1076*(1), 116–128. http://doi.org/10.1016/j.brainres.2005.11.074
Correa, Á., Lupiáñez, J., & Tudela, P. (2005). Attentional preparation based on temporal expectancy modulates processing at the perceptual level. *Psychonomic Bulletin & Review*, *12*(2), 328–34. http://doi.org/10.3758/BF03196380
Correa, Á., & Nobre, A. C. (2008). Neural modulation by regularity and passage of time. *Journal of Neurophysiology*, *9*, 1649–1655. http://doi.org/10.1152/jn.90656.2008
Cotti, J., Rohenkohl, G., Stokes, M., Nobre, A. C., & Coull, J. T. (2011). Functionally dissociating temporal and motor components of response preparation in left intraparietal sulcus. *NeuroImage*, *54*(2), 1221–1230.

http://doi.org/10.1016/j.neuroimage.2010.09.038
Coull, J. T., Davranche, K., Nazarian, B., & Vidal, F. (2013). Functional anatomy of timing differs for production versus prediction of time intervals. *Neuropsychologia*, *51*(2), 309–319. http://doi.org/10.1016/j.neuropsychologia.2012.08.017
Coull, J. T., Frith, C. D., Büchel, C., & Nobre, A. C. (2000). Orienting attention in time: Behavioural and neuroanatomical distinction between exogenous and endogenous shifts. *Neuropsychologia*, *38*(6), 808–819. http://doi.org/10.1016/S0028-3932(99)00132-3
Coull, J. T., & Nobre, A. C. (1998). Where and when to pay attention: the neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *The Journal of Neuroscience*, *18*(18), 7426–35. http://doi.org/0270-6474/98/187426-10$05.00/0
Coull, J. T., & Nobre, A. C. (2008). Dissociating explicit timing from temporal expectation with fMRI. *Current Opinion in Neurobiology*, *18*(2), 137–144. http://doi.org/10.1016/j.conb.2008.07.011
Coyle, S. M., Ward, E., & Markham, C. M. (2007). Brain – computer interface using a simplified functional near-infrared spectroscopy system. *Journal of Neural Engineering*, *219*(4), 219–226. http://doi.org/10.1088/1741-2560/4/3/007
Cravo, A. M., Rohenkohl, G., Wyart, V., & Nobre, A. C. (2011). Endogenous modulation of low frequency oscillations by temporal expectations. *Journal of Neurophysiology*, *106*(6), 2964–2972. http://doi.org/10.1152/jn.00157.2011
Cravo, A. M., Rohenkohl, G., Wyart, V., & Nobre, A. C. (2013). Temporal Expectation Enhances Contrast Sensitivity by Phase Entrainment of Low-Frequency Oscillations in Visual Cortex. *Journal of Neuroscience*, *33*(9), 4002–4010. http://doi.org/10.1523/JNEUROSCI.4675-12.2013
D'Albis, T., Blatt, R., Tedesco, R., Sbattella, L., & Matteucci, M. (2012). A predictive speller controlled by a Brain-Computer Interface based on motor imagery. *ACM Transactions on Computer-Human Interaction*, *19*(3), 1–25. http://doi.org/10.1145/2362364.2362368
Dal Seno, B., Matteucci, M., & Mainardi, L. T. (2010). The utility metric : A novel method to assess the overall performance of discrete Brain–Computer Interfaces. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *18*(1), 20–28. http://doi.org/10.1109/TNSRE.2009.2032642
Davranche, K., Nazarian, B., Vidal, F., & Coull, J. T. (2011). Orienting attention in time activates left intraparietal sulcus for both perceptual and motor task goals. *Journal of Cognitive Neuroscience*, *23*(11), 3318–3330. http://doi.org/10.1162/jocn_a_00030
de Graaf, T. A., Gross, J., Paterson, G., Rusch, T., Sack, A. T., & Thut, G. (2013). Alpha-band rhythms in visual task performance : Phase-locking by rhythmic sensory stimulation. *PLoS ONE*, *8*(3), 29–32. http://doi.org/10.1371/journal.pone.0060035
Dehaene, S., Bossini, S., & Giraux, P. (1993). The Mental representation of Parity and Number Magnitude. *Journal of Experimental Psychology. General*, *122*(3), 317–396.
Dehaene, S., Spelke, E. S., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of Mathematical Thinking: Behavioral and Brain Imaging Evidence. *Science*, *284*(5416), 970–974. http://doi.org/10.1126/science.284.5416.970
Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. http://doi.org/10.1016/j.jneumeth.2003.10.009
Desimone, R., & Duncan, J. (1995). Neural Mechanisms of Selective Visual. *Annual Review of Neuroscience*, *18*(1), 193–222. http://doi.org/10.1146/annurev.ne.18.030195.001205
Deutschländer, A., Marx, E., Stephan, T., Riedel, E., Wiesmann, M., Dieterich, M., & Brandt,

T. (2005). Asymmetric modulation of human visual cortex activity during 10° lateral gaze (fMRI study). *NeuroImage*, *28*(1), 4–13. http://doi.org/10.1016/j.neuroimage.2005.06.001

Ding, J., Sperling, G., & Srinivasan, R. (2006). Attentional modulation of SSVEP power depends on the network tagged by the flicker frequency. *Cerebral Cortex*, *16*(7), 1016–29. http://doi.org/10.1093/cercor/bhj044

Dodd, M. D., Van der Stigchel, S., Leghari, M. A., Fung, G., & Kingstone, A. (2008). Attentional SNARC: There's something special about numbers (let us count the ways). *Cognition*, *108*(3), 810–818. http://doi.org/10.1016/j.cognition.2008.04.006

Doherty, J. R., Rao, A., Mesulam, M. M., & Nobre, A. C. (2005). Synergistic effect of combined temporal and spatial expectations on visual attention. *The Journal of Neuroscience*, *25*(36), 8259–8266. http://doi.org/10.1523/JNEUROSCI.1821-05.2005

Donchin, E., Spencer, K. M., & Wijesinghe, R. (2000). The mental prosthesis: Assessing the speed of a P300-based brain- computer interface. *IEEE Transactions on Rehabilitation Engineering*, *8*(2), 174–179. http://doi.org/10.1109/86.847808

Dornhege, G., Krauledat, M., Müller, K.-R., & Blankertz, B. (2007). General signal processing and machine learning tools for BCI. In G. Dornhege, J. Del R Millán, T. Hinterberger, D. McFarland, & K.-R. Müller (Eds.), *Toward BrainComputer Interfacing* (pp. 207–234). London, UK: MIT Press. Retrieved from http://eprints.pascal-network.org/archive/00003322/

Dugué, L., Roberts, M., & Carrasco, M. (2016). Attention Reorients Periodically. *Current Biology*, *26*(12), 1595–1601. http://doi.org/10.1016/j.cub.2016.04.046

Dunlop, M. D., & Crossan, A. (2000). Predictive text entry methods for mobile phones. *Personal Technologies*, *4*(2–3), 134–143. http://doi.org/10.1007/BF01324120

Egan, J. P., Greenberg, G. Z., & Schulman, A. I. (1961). Interval of time uncertainty in auditory detection. *The Journal of the Acoustical Society of America*, *33*(6), 771–778. http://doi.org/10.1121/1.1908795

Ergenoglu, T., Demiralp, T., Bayraktaroglu, Z., Ergen, M., Beydagi, H., & Uresin, Y. (2004). Alpha rhythm of the EEG modulates visual detection performance in humans. *Cognitive Brain Research*, *20*(3), 376–383. http://doi.org/10.1016/j.cogbrainres.2004.03.009

Farwell, L., & Donchin, E. (1988). Talking off the top of your head: Toward a mental prosthesis utilizing Event-related brain potentials. *Electroencephalography and Clinical Neurophysiology*, *70*(6), 510–23. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/2461285

Fattorini, E., Pinto, M., Rotondaro, F., & Doricchi, F. (2015). Perceiving numbers does not cause automatic shifts of spatial attention. *Cortex*, *73*, 298–316. http://doi.org/10.1016/j.cortex.2015.09.007

Fazel-rezai, R., & Abhari, K. (2009). A region-based P300 speller for Brain-Computer Interface. *Can. J. Elect. Comput. Eng*, *34*(3), 81–85. http://doi.org/10.1109/CJECE.2009.5443854

Fazel-Rezai, R., Allison, B. Z., Guger, C., Sellers, E. W., Kleih, S. C., & Kübler, A. (2012). P300 brain computer interface: current challenges and emerging trends. *Frontiers in Neuroengineering*, *5*(July), 1–14. http://doi.org/10.3389/fneng.2012.00014

Felton, E. A., Member, S., Lewis, N. L., Wills, S. A., Radwin, R. G., Member, S., & Williams, J. C. (2007). Neural signal based control of the Dasher writing system. In *Proceedings of the 3rd International IEEE EMBS Conference on Neural Engineering* (pp. 366–370). Kohala Coast, Hawaii.

Fias, W., Brysbaert, M., Geypens, F., & d'Ydewalle, G. (1996). The importance of magnitude information in numerical processing: Evidence from the SNARC effect. *Mathematical*

Cignition, *2*(1), 995–110.
Fias, W., & Fischer, M. (2004a). *Spatial representation of number*. *Handbook of Mathematical Cognition*. http://doi.org/10.4324/9780203998045.ch3
Fias, W., & Fischer, M. H. (2004b). Spatial Representation of numbers. In J. I. D. Campbell (Ed.), *Handbook of Mathematical Cognition* (pp. 43–54). Routledge. http://doi.org/10.4324/9780203998045.ch3
Fias, W., Lauwereyns, J., & Lammertyn, J. (2001). Irrelevant digits affect feature-based attention depending on the overlap of neural circuits. *Cognitive Brain Research*, *12*, 415–423.
Fischer, M. H. (2001). Number processing induces spatial performance biases. *Neurology*, *57*(5), 822–826. http://doi.org/10.1212/WNL.57.5.822
Fischer, M. H. (2003). Spatial representations in number processing - Evidence from a pointing task. *Visual Cognition*, *10*(4), 493–508. http://doi.org/10.1080/13506280244000186
Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience*, *6*(6), 555–6. http://doi.org/10.1038/nn1066
Fischer, M. H., Warlop, N., Hill, R. L., & Fias, W. (2004). Oculomotor Bias Induced by Number Perception. *Experimental Psychology*, *51*(2), 91–97. http://doi.org/10.1027/1618-3169.51.2.91
Fitts, P. M., & Seeger, C. M. (1953). S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*(3), 199–210.
Folk, C., Remington, R., & Johnston, J. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(4), 1030–1044.
Freund, H. J. (2001). The parietal lobe as a sensorimotor interface: A perspective from clinical and neuroimaging data. *NeuroImage*, *14*(1 II), 142–146. http://doi.org/10.1006/nimg.2001.0863
Friesen, C., & Kingstone, A. (1998). The eyes have it! reflexive orienting is triggered by nonpredictive gaze - download. *Psychonomic Bulletin and Review*, *5*(3), 490–495. http://doi.org/10.3758/BF03208827
Friman, O., Friman, O., Volosyak, I., Volosyak, I., Gräser, A., & Gräser, A. (2007). Multiple channel detection of steady-state visual evoked potentials for Brain-Computer Interfaces. *IEEE Transactions on Biomedical Engineering*, *54*(4), 742–50. http://doi.org/10.1109/TBME.2006.889160
Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized Timing of Isochronous Sounds Is Represented in Neuromagnetic Beta Oscillations. *Journal of Neuroscience*, *32*(5), 1791–1802. http://doi.org/10.1523/JNEUROSCI.4107-11.2012
Galfano, G., Rusconi, E., & Umiltà, C. (2006). Number magnitude orients attention, but not against one's will. *Psychonomic Bulletin & Review*, *13*(5), 869–74. http://doi.org/10.3758/BF03194011
Garcia-Molina, G., & Zhu, D. (2011). Optimal spatial filtering for the steady state visual evoked potential: BCI application. In *2011 5th International IEEE/EMBS Conference on Neural Engineering* (pp. 156–160). Cancun, Mexico. http://doi.org/10.1109/NER.2011.5910512
Garcia, J. O., Srinivasan, R., & Serences, J. T. (2013). Near-real-time feature-selective modulations in human cortex. *Current Biology*, *23*(6), 515–522. http://doi.org/https://10.1016/j.cub.2013.02.013
Gevers, W., Caessens, B., & Fias, W. (2005). Towards a common processing architecture underlying Simon and SNARC effects. *European Journal of Cognitive Psychology*, *17*(5),

659–673. http://doi.org/10.1080/09541440540000112
Gevers, W., Lammertyn, J., Notebaert, W., Verguts, T., & Fias, W. (2006). Automatic response activation of implicit spatial information: Evidence from the SNARC effect. *Acta Psychologica*, *122*(3), 221–233. http://doi.org/10.1016/j.actpsy.2005.11.004
Gevers, W., Ratinckx, E., De Baene, W., & Fias, W. (2006). Further evidence that the SNARC effect is processed along a dual-route architectures: Evidence from the lateralized readiness potential. *Experimental Psychology*, *53*(1), 58–68. http://doi.org/10.1027/1618-3169.53.1.58
Gevers, W., Verguts, T., Reynvoet, B., Caessens, B., & Fias, W. (2006). Numbers and space: A computational model of the SNARC effect. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(1), 32–44. http://doi.org/10.1037/0096-1523.32.1.32
Göbel, S. M., Calabria, M., Farnè, A., & Rossetti, Y. (2006). Parietal rTMS distorts the mental number line: Simulating “spatial” neglect in healthy subjects. *Neuropsychologia*, *44*(6), 860–868. http://doi.org/10.1016/j.neuropsychologia.2005.09.007
Goffaux, V., Martin, R., Dormal, G., Goebel, R., & Schiltz, C. (2012). Attentional shifts induced by uninformative number symbols modulate neural activity in human occipital cortex. *Neuropsychologia*, *50*(14), 3419–3428. http://doi.org/10.1016/j.neuropsychologia.2012.09.046
GoQ Software. (n.d.). Retrieved July 30, 2013, from http://www.goqsoftware.com/
Gould, I. C., Rushworth, M. F., & Nobre, A. C. (2011). Indexing the graded allocation of visuospatial attention using anticipatory alpha oscillations. *Journal of Neurophysiology*, *105*(3), 1318–26. http://doi.org/10.1152/jn.00653.2010
Graimann, B., Allison, B., & Pfurtscheller, G. (2010). Brain-Computer Interfaces: A gentle introduction. In B. Graimann, G. Pfurtscheller, & B. Allison (Eds.), *Brain-Computer Interfaces* (pp. 1–27). Berlin, Heidelberg: Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-642-02091-9
Griffin, I. C., Miniussi, C., & Nobre, A. C. (2001). Orienting attention in time. *Frontiers in Bioscience*, *6*(12), D660–D671. http://doi.org/10.2741/Griffin
Griffin, I. C., Miniussi, C., & Nobre, A. C. (2002). Multiple mechanisms of selective attention: Differential modulation of stimulus processing by attention to space or time. *Neuropsychologia*, *40*(13), 2325–2340. http://doi.org/10.1016/S0028-3932(02)00087-8
Guan, C., Thulasidas, M., & Wu, J. (2004). High performance P300 speller for Brain-Computer Interface. In *IEEE International Workshop on Biomedical Circuits and Systems, 2004.* (pp. 293–296). IEEE. http://doi.org/10.1109/BIOCAS.2004.1454155
Gulbinaite, R., Johnson, A., de Jong, R., Morey, C. C., & van Rijn, H. (2014). Dissociable mechanisms underlying individual differences in visual working memory capacity. *NeuroImage*, *99*, 197–206. http://doi.org/10.1016/j.neuroimage.2014.05.060
Gulbinaite, R., van Viegen, T., Wieling, M., Cohen, M. X., & VanRullen, R. (2017). Individual alpha peak frequency predicts 10 Hz flicker effects on selective attention. *The Journal of Neuroscience*, *37*(42), 1163–17. http://doi.org/10.1523/JNEUROSCI.1163-17.2017
Guo, F., Hong, B., Gao, X., & Gao, S. (2008). A Brain-Computer Interface using motion-onset visual evoked potential. *Journal of Neural Engineering*, *5*(4), 477–485. http://doi.org/10.1088/1741-2560/5/4/011
Gut, M., Szumska, I., Wasilewska, M., & Jaśkowski, P. (2012). Are low and high number magnitudes processed differently while resolving the conflict evoked by the SNARC effect? *International Journal of Psychophysiology*, *85*(1), 7–16. http://doi.org/10.1016/j.ijpsycho.2012.02.007
Guzman-Martinez, E., Grabowecky, M., Palafox, G., & Suzuki, S. (2012). A unique role of

endogenous visual-spatial attention in rapid processing of multiple targets. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(1), 1–15. http://doi.org/10.1080/10447318.2011.535754.Predictive

Handy, T. . C. (2005). *Event-related potential: A methods handbook*. (T. . C. Handy, Ed.). The MIT Press.

Hanslmayr, S., Aslan, A., Staudigl, T., Klimesch, W., Herrmann, C. S., & Bäuml, K. H. (2007). Prestimulus oscillations predict visual perception performance between and within subjects. *NeuroImage*, *37*(4), 1465–1473. http://doi.org/10.1016/j.neuroimage.2007.07.011

Harvey, B. M., Kelin, B. P., Petridou, B. P., Dumoulin, S. O., Klein, B. P., Petridou, N., & Dumoulin, S. O. (2013). Topographic representation of numerosity in the human parietal cortex. *Science*, *341*(september), 1123–1126. http://doi.org/10.1126/science.1239052

Heinrich, S. P. (2007). A primer on motion visual evoked potentials. *Documenta Ophthalmologica*, *114*(2), 83–105. http://doi.org/10.1007/s10633-006-9043-8

Henry, M. J., & Obleser, J. (2012). Frequency modulation entrains slow neural oscillations and optimizes human listening behavior. *Proceedings of the National Academy of Sciences*, *109*(49), 20095–20100. http://doi.org/10.1073/pnas.1213390109

Herrmann, C. S. (2001). Human EEG responses to 1-100 Hz flicker: Resonance phenomena in visual cortex and their potential correlation to cognitive phenomena. *Experimental Brain Research*, *137*(3–4), 346–353. http://doi.org/10.1007/s002210100682

Hesse, P. N., & Bremmer, F. (2017). The SNARC effect in two dimensions: Evidence for a frontoparallel mental number plane. *Vision Research*, *130*, 85–96. http://doi.org/10.1016/j.visres.2016.10.007

Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). 3) Electrophysiological Evidence of the Capture of Visual Attention. *Journal of Cognitive Neuroscience*, *18*(4), 604–613. http://doi.org/10.1162/jocn.2006.18.4.604

Hietanen, J. K., Leppänen, J. M., Nummenmaa, L., & Astikainen, P. (2008). Visuospatial attention shifts by gaze and arrow cues: An ERP study. *Brain Research*, *1215*, 123–136. http://doi.org/10.1016/j.brainres.2008.03.091

Higashi, H., & Tanaka, T. (2013). Simultaneous design of FIR filter banks and spatial patterns for EEG signal classification. *IEEE Transactions on Biomedical Engineering*, *60*(4), 1100–1110. http://doi.org/10.1109/TBME.2012.2215960

Hillyard, S. A., & Anllo-Vento, L. (1998). Event-related brain potentials in the study of visual selective attention. *Proceedings of the National Academy of Sciences of the United States of America*, *95*(3), 781–787. http://doi.org/10.1073/pnas.95.3.781

Hillyard, S. A., Hinrichs, H., Tempelmann, C., Morgan, S. T., Hansen, J. C., Scheich, H., & Heinze, H. J. (1997). Combining steady-state visual evoked potentials and f MRI to localize brain activity during selective attention. *Human Brain Mapping*, *5*(4), 287–292. http://doi.org/10.1002/(SICI)1097-0193(1997)5:4<287::AID-HBM14>3.0.CO;2-B

Hintermüller, C., Guger, C., & Edlinger, G. (2011). Brain-Computer Interface: Generic control interface for social interaction applications. In J. Cabestany, I. Rojas, & G. Joya (Eds.), *Advances in Computational Intelligence* (pp. 386–392). Torremolinos-Málaga, Spain: Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-642-21501-8_48

Höhne, J., Schreuder, M., Blankertz, B., & Tangermann, M. (2011). A novel 9-class auditory ERP paradigm driving a predictive text entry system. *Frontiers in Neuroscience*, *5*(August), 99. http://doi.org/10.3389/fnins.2011.00099

Hommel, B., Pratt, J., Colzato, L., & Godijn, R. (2015). Symbolic control of visual attention. *Psychological Science*, *6*(1), 101–104. http://doi.org/10.7897/2277-4343.06122

Hong, B., Guo, F., Liu, T., Gao, X., & Gao, S. (2009). N200-speller using motion-onset visual response. *Clinical Neurophysiology*, *120*(9), 1658–1666. http://doi.org/10.1016/j.clinph.2009.06.026

Hopfinger, J. B., Buonocore, M. H., & Mangun, G. R. (2000). The neural mechanisms of top-down attentional control. *Nature Neuroscience*, *3*(3), 284–291. http://doi.org/10.1038/72999

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews. Neuroscience*, *6*(6), 435–48. http://doi.org/10.1038/nrn1684

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2009). Numerical and Spatial Intuitions: A Role for Posterior Parietal Cortex? *Cognitive Biology: Evolutionary and Developmental Perspectives on Mind, Brain and Behavior*, *11*, 221–246.

Huddleston, W. E., & DeYoe, E. A. (2008). The representation of spatial attention in human parietal cortex dynamically modulates with performance. *Cerebral Cortex*, *18*(6), 1272–1280. http://doi.org/10.1093/cercor/bhm158

Jackson, A. F., & Bolger, D. J. (2014). The neurophysiological bases of EEG and EEG measurement: A review for the rest of us. *Psychophysiology*, *51*, 1061–1071. http://doi.org/10.1111/psyp.12283

Jamison, K. W., Roy, A. V, He, S., Engel, S. A., & He, B. (2015). SSVEP signatures of binocular rivalry during simultaneous EEG and fMRI. *Journal of Neuroscience Methods*, *243*, 53–62. http://doi.org/10.1016/j.jneumeth.2015.01.024

Janssen, P., & Shadlen, M. N. (2005). A representation of the hazard rate of elapsed time in macaque area LIP. *Nature Neuroscience*, *8*(2), 234–241. http://doi.org/10.1038/nn1386

Jarick, M., Dixon, M. J., Maxwell, E. C., Nicholls, M. E. R., & Smilek, D. (2009). The ups and downs (and lefts and rights) of synaesthetic number forms: Validation from spatial cueing and SNARC-type tasks. *Cortex*, *45*(10), 1190–1199. http://doi.org/10.1016/j.cortex.2009.04.015

Jepma, M., Wagenmakers, E. J., & Nieuwenhuis, S. (2012). Temporal expectation and information processing: A model-based analysis. *Cognition*, *122*(3), 426–441. http://doi.org/10.1016/j.cognition.2011.11.014

Jia, C., Gao, X., Hong, B., & Gao, S. (2011). Frequency and phase mixed coding in SSVEP-based Brain-Computer Interface. *IEEE Transactions on Biomedical Engineering*, *58*(1), 200–206. http://doi.org/10.1109/TBME.2010.2068571

Jia, J., Liu, L., Fang, F., & Luo, H. (2017). Sequential sampling of visual objects during sustained attention. *PLoS Biology*, *15*(6), 1–19. http://doi.org/10.1371/journal.pbio.2001903

Jin, J., Allison, B. Z., Brunner, C., Wang, B., Wang, X., Zhang, J., … Pfurtscheller, G. (2010). P300 Chinese input system based on Bayesian LDA. *Biomedizinische Technik. Biomedical Engineering*, *55*(1), 5–18. http://doi.org/10.1515/BMT.2010.003

Jin, J., Allison, B. Z., Wang, X., & Neuper, C. (2012). A combined brain-computer interface based on P300 potentials and motion-onset visual evoked potentials. *Journal of Neuroscience Methods*, *205*(2), 265–76. http://doi.org/10.1016/j.jneumeth.2012.01.004

Jones, M. R. (1976). Time, our lost dimension: toward a new theory of perception, attention, and memory. *Psychological Review*, *83*(5), 323–355. http://doi.org/10.1037/0033-295X.83.5.323

Jones, M. R., Moynihan, H., MacKenzie, N., & Puente, J. (2002). Temporal aspects of stimulus-driven attending in dynamic arrays. *Psychological Science*, *13*(4), 313–319. http://doi.org/10.1111/j.0956-7976.2002.00458.x

Kapeller, C., Hintermüller, C., Abu-Alqumsan, R., Prückl, R., Peer, A., & Guger, C. (2013). A

BCI using VEP for continuous control of a mobile robot. In *Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (pp. 5254–5257). Osaka, Japan.

Kashiwase, Y., Matsumiya, K., Kuriki, I., & Shioiri, S. (2012). Time courses of attentional modulation in neural amplification and synchronization measured with steady-state visual-evoked potentials. *Journal of Cognitive Neuroscience*, *24*(8), 1779–1793. http://doi.org/10.1162/jocn_a_00212

Kaufmann, T., Völker, S., Gunesch, L., & Kübler, A. (2012). Spelling is just a click away - A user-centered Brain-Computer Interface including auto-calibration and predictive text entry. *Frontiers in Neuroscience*, *6*(May), 72. http://doi.org/10.3389/fnins.2012.00072

Keil, A., & Heim, S. (2009). Prolonged reduction of electrocortical activity predicts correct performance during rapid serial visual processing. *Psychophysiology*, *46*(4), 718–725. http://doi.org/10.1111/j.1469-8986.2009.00824.x

Keitel, X. C., Quigley, X. C., & Ruhnau, X. P. (2014). Stimulus-Driven Brain Oscillations in the Alpha Range : Entrainment of Intrinsic Rhythms or Frequency-Following Response ?, *34*(31), 10137–10140. http://doi.org/10.1523/JNEUROSCI.1904-14.2014

Keus, I. M., Jenks, K. M., & Schwarz, W. (2005). Psychophysiological evidence that the SNARC effect has its functional locus in a response selection stage. *Cognitive Brain Research*, *24*(1), 48–56. http://doi.org/10.1016/j.cogbrainres.2004.12.005

Keus, I. M., & Schwarz, W. (2005). Searching for the functional locus of the SNARC effect: evidence for a response-related origin. *Memory & Cognition*, *33*(4), 681–695. http://doi.org/10.3758/BF03195335

Khorshidtalab, A., & Salami, M. J. E. (2011). EEG Signal Classification for real-time Brain-Computer Interface applications : A review. In *International Conference on Mechatronics (ICOM)* (pp. 17–19). Kuala Lumpur, Malaysia: Ieee. http://doi.org/10.1109/ICOM.2011.5937154

Kim, Y. J., Grabowecky, M., Paller, K. A., Muthu, K., & Suzuki, S. (2007). Attention induces synchronization-based response gain in steady-state visual evoked potentials. *Nature Neuroscience*, *10*(1), 117–125. http://doi.org/10.1038/nn1821

Kindermans, P.-J., Verschore, H., Verstraeten, D., & Schrauwen, B. (2012). A P300 BCI for the masses: Prior information enables instant unsupervised spelling. In P. Bartlett, F. C. N. Pereira, C. J. C. Burges, L. Bottou, & K. Q. Weinberger (Eds.), *Advances in Neural Information Processing Systems 25* (pp. 719–727). Lake Tahoe, Canada: NIPS Foundation. Retrieved from http://books.nips.cc/papers/files/nips25/NIPS2012_0332.pdf

Kleiner, M., Brainard, D. H., & Pelli, D. (2007). “Whats new in Psychtoolbox-3?” In *Thirtieth European Conference on Visual Perception* (Vol. 36, pp. 1–235). Arezzo.

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences*, *16*(12), 606–617. http://doi.org/10.1016/j.tics.2012.10.007

Klimesch, W., Doppelmayr, M., Russegger, H., Pachinger, T., & Schwaiger, J. (1998). Induced alpha band power changes in the human EEG and attention. *Neuroscience Letters*, *244*(2), 73–76. http://doi.org/10.1016/S0304-3940(98)00122-0

Koester, H. H., & Levine, S. P. (1994). Learning and performance of able-bodied individuals using scanning systems with and without word prediction. *Assistive Technology*, *6*(1), 42–53. http://doi.org/10.1080/10400435.1994.10132226

Konrad, P., & Shanks, T. (2010). Implantable Brain Computer Interface: Challenges to neurotechnology translation. *Neurobiology of Disease*, *38*(3), 369–375. http://doi.org/10.1016/j.nbd.2009.12.007

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: cognitive basis for stimulus-response compatibility-A model and taxonomy. *Psychological Review*, *97*(2), 253–270. http://doi.org/10.1037/0033-295X.97.2.253

Krusienski, D. J., Grosse-Wentrup, M., Galán, F., Coyle, D., Miller, K. J., Forney, E., & Anderson, C. W. (2011). Critical issues in state-of-the-art brain-computer interface signal processing. *Journal of Neural Engineering*, *8*(2), 25002. http://doi.org/10.1088/1741-2560/8/2/025002

Kuba, M., Kubová, Z., Kremláček, J., & Langrová, J. (2007). Motion-onset VEPs: Characteristics, methods, and diagnostic use. *Vision Research*, *47*(2), 189–202. http://doi.org/10.1016/j.visres.2006.09.020

Lampar, A., & Lange, K. (2011). Effects of temporal trial-by-trial cuing on early and late stages of auditory processing: Evidence from event-related potentials. *Attention, Perception, & Psychophysics*, *73*(6), 1916–1933. http://doi.org/10.3758/s13414-011-0149-z

Lange, K. (2010). Can a regular context induce temporal orienting to a target sound? *International Journal of Psychophysiology*, *78*(3), 231–238. http://doi.org/10.1016/j.ijpsycho.2010.08.003

Lange, K., Krämer, U. M., & Röder, B. (2006). Attending points in time and space. *Experimental Brain Research*, *173*(1), 130–140. http://doi.org/10.1007/s00221-006-0372-3

Lange, K., Rösler, F., & Röder, B. (2003). Early processing stages are modulated when auditory stimuli are presented at an attended moment in time: An event-related potential study. *Psychophysiology*, *40*(5), 806–817. http://doi.org/10.1111/1469-8986.00081

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, *106*(1), 119–159.

Lasley, D. J., & Cohn, T. (1981). Detection of a luminance increment: Effect of temporal uncertainty. *Journal of the Optical Society of America*, *71*(7), 845. http://doi.org/10.1364/JOSA.71.000845

Leon, M. I., & Shadlen, M. N. (2003). Representation of time by neurons in the posterior parietal cortex of the Macaque. *Neuron*, *38*(2), 317–327. http://doi.org/10.1016/S0896-6273(03)00185-5

Li, P., Xu, P., Zhang, R., Guo, L., & Yao, D. (2013). L1 Norm based common spatial patterns decomposition for scalp EEG BCI. *BioMedical Engineering Online*, *12*(1), 1. http://doi.org/10.1186/1475-925X-12-77

Lima, B., Singer, W., & Neuenschwander, S. (2011). Gamma responses correlate with temporal expectation in monkey primary visual cortex. *Journal of Neuroscience*, *31*(44), 15919–15931. http://doi.org/10.1523/JNEUROSCI.0957-11.2011

Liotti, M., Dazzi, S., & Umiltà, C. (1993). Deficits of the automatic orienting of attention in schizophrenic patients. *Journal of Psychiatric Research*, *27*(1), 119–130. http://doi.org/10.1016/0022-3956(93)90056-8

Liu, T., Goldberg, L., Gao, S., & Hong, B. (2010). An online Brain-Computer Interface using non-flashing visual evoked potentials. *Journal of Neural Engineering*, *7*(3). http://doi.org/10.1088/1741-2560/7/3/036003

Logan, G. D. (1996). The CODE theory of visual attention: An intergration of space-based and object-based attention. *Psychological Review*, *103*(4), 603–649.

Los, S. A., & Agter, F. (2005). Reweighting sequential effects across different distributions of foreperiods: segregating elementary contributions to nonspecific preparation. *Perception & Psychophysics*, *67*(7), 1161–1170. http://doi.org/10.3758/BF03193549

Los, S. A., Knol, D. L., & Boers, R. M. (2001). The foreperiod effect revisited : Conditioning as a basis for nonspecific preparation. *Acta*, *106*, 121–145.

Lotte, F., Congedo, M., Lécuyer, A., Lamarche, F., & Arnaldi, B. (2007). A review of classification algorithms for EEG-based brain-computer interfaces. *Journal of Neural Engineering*, *4*(2). http://doi.org/10.1088/1741-2560/4/2/R01

Lowe, G. (1967). Interval of time uncertainty in visual detection. *Perception & Psychophysics*, *2*(7), 278–280. http://doi.org/10.3758/BF03211041

Luck, S. J. (2005a). *An Introduction to event-related potentials and their neural origins*. *An introduction to the event-related potential technique*. Michigan, MA, USA: MIT Press. http://doi.org/10.1007/s10409-008-0217-3

Luck, S. J. (2005b). *An introduction to the event-related potential technique*. (M. Gazzaniga, Ed.). Cambridge, MA: MIT Press. http://doi.org/10.1016/B978-0-12-386986-9.00014-4

Luck, S. J., & Kappenman, E. S. (2012). ERP Components and Selective Attention. In S. J. Luck & E. S. Kappenman (Eds.), *The Oxford Handbook of Event-Related Potential Components* (pp. 1–54). Oxford: Oxford University Press. http://doi.org/10.1093/oxfordhb/9780195374148.001.0001

Mak, J. N., Arbel, Y., Minett, J. W., McCane, L. M., Yuksel, B., Ryan, D., … Erdogmus, D. (2011). Optimizing the P300-based brain-computer interface: current status, limitations and future directions. *Journal of Neural Engineering*, *8*(2), 25003. http://doi.org/10.1088/1741-2560/8/2/025003

Mak, J. N., & Wolpaw, J. R. (2009). Clinical applications of Brain-Computer Interfaces: Current state and future prospects. *IEEE Reviews in Biomedical Engineering*. IEEE. http://doi.org/10.1109/RBME.2009.2035356

Malinowski, P., Fuchs, S., & Müller, M. M. (2007). Sustained division of spatial attention to multiple locations within one hemifield. *Neuroscience Letters*, *414*(1), 65–70. http://doi.org/10.1016/j.neulet.2006.12.001

Manyakov, N. V., Chumerin, N., Combaz, A., & Van Hulle, M. M. (2011). Comparison of classification methods for P300 Brain-Computer Interface on disabled subjects. *Computational Intelligence and Neuroscience*, *2011*. http://doi.org/doi:10.1155/2011/519868

Manyakov, N. V, Chumerin, N., Combaz, A., Robben, A., & Van Hulle, M. M. (2010). Decoding SSVEP responses using time domain classification. In *International Conference on Fuzzy Computation and 2nd International Conference on Neural Computation* (pp. 376–380). Valencia, Spain. http://doi.org/10.5220/0003106103760380

Manyakov, N. V, Chumerin, N., Robben, A., Combaz, A., van Vliet, M., & Van Hulle, M. M. (2013). Sampled sinusoidal stimulation profile and multichannel fuzzy logic classification for monitor-based phase-coded SSVEP Brain-Computer Interfacing. *Journal of Neural Engineering*, *10*(3), 36011. http://doi.org/10.1088/1741-2560/10/3/036011

Manyakov, N. V, Chumerin, N., & Van Hulle, M. M. (2012). Multichannel decoding for phase-coded ssvep brain-computer interface. *International Journal of Neural Systems*, *22*(5), 1250022. http://doi.org/10.1142/S0129065712500220

Mapelli, D., Rusconi, E., & Umiltà, C. (2003). The SNARC effect: an instance of the Simon effect? *Cognition*, *88*(4), 1–10. http://doi.org/10.1016/S0

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. http://doi.org/10.1016/j.jneumeth.2007.03.024

Marslen-Wilson, W. D. (1987). Functional parallelism in spoken word-recognition. *Cognition*, *25*(1–2), 71–102. http://doi.org/10.1016/0010-0277(87)90005-9

Mathewson, K. E., Fabiani, G., Monica, G., Beck, D. M., & Lleras, A. (2010). Making waves in the stream of consciousness: Eliciting predictable oscillations in visual awareness with pretarget entrainment at 12 Hz. In M. Brooks, Joseph, Belopolsky, Artem, Matsukura, Michi and Palomares (Ed.), *Object Perception, Attention, and Memory (OPAM) 2009 Conference Report 17th Annual Meeting, Boston, MA, USA* (Vol. 18, pp. 137–141). Boston, Machassusetts: Psychology Press. http://doi.org/10.1080/13506280903314433

Mathewson, K. E., Fabiani, M., Gratton, G., Beck, D. M., & Lleras, A. (2010). Rescuing stimuli from invisibility: Inducing a momentary release from visual masking with pre-target entrainment. *Cognition*, *115*(1), 186–191. http://doi.org/10.1016/j.cognition.2009.11.010

Mathewson, K. E., Gratton, G., Fabiani, M., Beck, D. M., & Ro, T. (2009). To see or not to see: Prestimulus alpha phase predicts visual awareness. *The Journal of Neuroscience*, *29*(9), 2725–2732. http://doi.org/10.1523/JNEUROSCI.3963-08.2009

Mathewson, K. E., Lleras, A., Beck, D. M., Fabiani, M., Ro, T., & Gratton, G. (2011). Pulsed out of awareness: EEG alpha oscillations represent a pulsed-inhibition of ongoing cortical processing. *Frontiers in Psychology*, *2*(May), 1–15. http://doi.org/10.3389/fpsyg.2011.00099

Mathewson, K. E., Prudhomme, C., Fabiani, M., Beck, D. M., Lleras, A., & Gratton, G. (2012). Making waves in the stream of consciousness: Entraining oscillations in EEG alpha and fluctuations in visual awareness with rhythmic visual stimulation. *Journal of Cognitive Neuroscience*, *24*(12), 2321–33. http://doi.org/10.1162/jocn_a_00288

Mathis, T., & Spohr, D. (2007). Corpus-driven enhancement of a BCI spelling component. In *International Conference on Recent Advances in Natural Language Processing (RANLP 2007)* (pp. 1–5). Borovets, Bulgaria. Retrieved from http://www.sc.cit-ec.uni-bielefeld.de/sites/www.sc.cit-ec.uni-bielefeld.de/files/ranlp07_mathisspohr.pdf

McFarland, D. J., McCane, L. M., David, S. V., & Wolpaw, J. R. (1997). Spatial filter selection for EEG-based communication. *Electroencephalography and Clinical Neurophysiology*, *103*(3), 386–394. http://doi.org/10.1016/S0013-4694(97)00022-2

Min, B.-K., Marzelli, M. J., & Yoo, S.-S. (2010). Neuroimaging-based approaches in the Brain-computer Interface. *Trends in Biotechnology*, *28*(11), 552–60. http://doi.org/10.1016/j.tibtech.2010.08.002

Miniussi, C., Wilding, E. L., Coull, J. T., & Nobre, A. C. (1999). Orienting attention in time. Modulation of brain potentials. *Brain*, *122*, 1507–1518. http://doi.org/10.1093/brain/122.8.1507

Montagna, B., Pestilli, F., & Carrasco, M. (2009). Attention trades off spatial acuity. *Vision Research*, *49*(7), 735–745. http://doi.org/10.1016/j.visres.2009.02.001

Mora-Cortes, A., Manyakov, N., Chumerin, N., & Van Hulle, M. (2014). Language model applications to spelling with brain-computer interfaces. *Sensors*, *14*(4), 5967–5993. http://doi.org/10.3390/s140405967

Morgan, S. T., Hansen, J. C., & Hillyard, S. A. (1996). Selective attention to stimulus location modulates the steady-state visual evoked potential. *Proceedings of the National Academy of Sciences of the United States of America*, *93*(10), 4770–4. http://doi.org/10.1073/pnas.93.10.4770

Moyer, R. S., & Landauer, T. K. (1967). Time required for Judgements of Numerical Inequality. *Nature*, *215*(5109), 1519–1520. http://doi.org/10.1038/2151519a0

Müller, D., & Schwarz, W. (2007). Exploring the mental number line: Evidence from a dual-task paradigm. *Psychological Research*, *71*(5), 598–613. http://doi.org/10.1007/s00426-006-0070-6

Müller, M. M., Andersen, S. K., Trujillo, N. J., Valdés-Sosa, P., Malinowski, P., & Hillyard, S. A. (2006). Feature-selective attention enhances color signals in early visual areas of the human brain. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(38), 14250–4. http://doi.org/10.1073/pnas.0606668103

Müller, M. M., & Hillyard, S. A. (2000). Concurrent recording of steady-state and transient event-related potentials as indices of visual-spatial selective attention. *Clinical Neurophysiology*, *111*(9), 1544–52. http://doi.org/10.1016/S1388-2457(00)00371-0

Müller, M. M., Malinowski, P., Gruber, T., & Hillyard, S. A. (2003). Sustained division of the attentional spotlight. *Nature*, *24*, 309–312. http://doi.org/10.1038/nature01744.1.

Müller, M. M., Picton, T. W., Valdes-Sosa, P., Riera, J., Teder-Sälejärvi, W. A., & Hillyard, S. A. (1998). Effects of spatial selective attention on the steady-state visual evoked potential in the 20-28 Hz range. *Cognitive Brain Research*, *6*(4), 249–61. http://doi.org/10.1016/S0926-6410(97)00036-0

Müller, M. M., Teder-Sälejärvi, W. A., & Hillyard, S. A. (1998). The time course of cortical facilitation during cued shifts of spatial attention. *Nature Neuroscience*, *1*(7), 631–634. http://doi.org/10.1038/2865

Müller, N. G., Bartelt, O. A., Donner, T. H., Villringer, A., & Brandt, S. A. (2003). A physiological correlate of the "Zoom Lens" of visual attention. *The Journal of Neuroscience*, *23*(9), 3561–3565. Retrieved from http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=12736325

Mun, S., Park, M., Park, S., & Whang, M. (2012). SSVEP and ERP measurement of cognitive fatigue caused by stereoscopic 3D. *Neuroscience Letters*, *525*, 89–94. Retrieved from http://dx.doi.org/10.1016/j.neulet.2012.07.049

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*(11), 1631–1647. http://doi.org/10.1016/0042-6989(89)90144-2

Nantais, T., Shein, F., & Johansson, M. (2001). Efficacy of the word prediction algorithm in WordQ. In *In Proceedings of the RESNA Annual Conference 2001* (pp. 77–79). Reno, NV, USA.

Navarro, A. A., Ceccaroni, L., Velickovski, F., Torrellas, S., Miralles, F., Allison, B. Z., … Faller, J. (2011). Context-awareness as an enhancement of Brain-Computer Interfaces. In J. Bravo, R. Hervas, & V. Villareal (Eds.), *International Workshop on Ambient Assisted Living* (pp. 216–223). Torremolinos-Málaga, Spain: Springer.

Nestor, P. G., Faux, S. F., McCarley, R. W., Penhune, V., Shenton, M. E., Pollak, S., & Sands, S. F. (1992). Attentional cues in chronic schizophrenia: Abnormal disengagement of attention. *Journal of Abnormal Psychology*, *101*(4), 682–689. http://doi.org/10.1037/0021-843X.101.4.682

Nicolas-Alonso, L. F., & Gomez-Gil, J. (2012). Brain computer interfaces, a review. *Sensors*, *12*(2), 1211–1279. http://doi.org/10.3390/s120201211

Niki, H., & Watanabe, M. (1979). Prefrontal and cingulate unit activity during timing behavior in the monkey. *Brain Research*, *171*, 213–224. http://doi.org/https://doi.org/10.1016/0006-8993(79)90328-7

Nobre, A. C. (2001). Orienting attention to instants in time. *Neuropsychologia*, *39*, 1317–1328.

Nobre, A. C. (2010). *Attention and time*. (A. C. Nobre & J. T. Coull, Eds.). Oxford, UK: Oxford University Press.

Nobre, A. C., & Rohenkohl, G. (2014). *Time for the Fourth Dimension in Attention*. *The Oxford Handbook of Attention*. http://doi.org/10.1093/oxfordhb/9780199675111.001.0001

Norcia, A. M., Appelbaum, G., Ales, J., Cottereau, B., & Rossion, B. (2015). The steady-state visual evoked potential in vision research : A review. *Journal of Vision*, *15*(6), 1–46. http://doi.org/10.1167/15.6.4.doi

Nuance Communications. (n.d.). Retrieved July 30, 2013, from http://www.nuance.com/

Orhan, U., Erdogmus, D., Roark, B., Purwar, S., Hild, K. E., Oken, B., & Nezamfar, H. (2011).

Fusion with language models improves spelling accuracy for Erp-Based Brain Computer Interface spellers. In *In Proceedings of the 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (pp. 1–4). Boston, MA, USA.

Ortner, R., Guger, C., Prueckl, R., Grünbacher, E., & Edlinger, G. (2010). SSVEP Based Brain-Computer Interface for robot control. In *International Conference on Computers Helping People with Special Needs* (pp. 85–90). Vienna, Austria: Springer. http://doi.org/10.1007/978-3-642-14100-3_14

Pasqualotto, E., Federici, S., & Belardinelli, M. O. (2012). Toward functioning and usable Brain – Computer Interfaces (BCIs): A literature review. *Disability and Rehabilitation: Assistive Technology*, *7*(2), 89–103. http://doi.org/https://doi.org/10.3109/17483107.2011.589486

Pastukhov, A., Fischer, L., & Braun, J. (2009). Visual attention is a single, integrated resource. *Vision Research*, *49*(10), 1166–1173. http://doi.org/10.1016/j.visres.2008.04.011

Pei, F., Pettet, M. W., & Norcia, A. M. (2002). Neural correlates of object-based attention. *Journal of Vision*, *2*(9), 1. http://doi.org/10.1167/2.9.1

Pelli, D. G. (1997). The Videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*. http://doi.org/10.1163/156856897X00366

Pestilli, F., & Carrasco, M. (2005). Attention enhances contrast sensitivity at cued and impairs it at uncued locations. *Vision Research*, *45*(14), 1867–1875. http://doi.org/10.1016/j.visres.2005.01.019

Pfurtscheller, G. (1977). Graphical display and statistical evaluation of event-related desynchronization (ERD). *Electroencephalography and Clinical Neurophysiology*, *43*(5), 757–760. http://doi.org/10.1016/0013-4694(77)90092-X

Pfurtscheller, G. (1992). Event-related synchronization (ERS): An electrophysiological correlate of cortical areas at rest. *Electroencephalography and Clinical Neurophysiology*, *83*(1), 62–69. http://doi.org/10.1016/0013-4694(92)90133-3

Pfurtscheller, G., & Lopes da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: Basic principles. *Clinical Neurophysiology*, *110*(11), 1842–1857. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10576479

Pfurtscheller, G., & Neuper, C. (2001). Motor imagery and direct brain- computer communication. *Proceedings of the IEEE*, *89*(7), 1123–1134. http://doi.org/10.1109/5.939829

Piazza, M., Mechelli, A., Butterworth, B., & Price, C. J. (2002). Are subitizing and counting implemented as separate or functionally overlapping processes? *NeuroImage*, *15*(2), 435–446. http://doi.org/10.1006/nimg.2001.0980

Pineda, J. A., Allison, B. Z., & Vankov, A. (2000). The effects of self-movement, observation, and imagination on mu rhythms and readiness potentials (RP's): Toward a Brain-Computer Interface (BCI). *IEEE Transactions on Rehabilitation Engineering*, *8*(2), 219–22. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10896193

Pinel, P., Piazza, M., Le Bihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. *Neuron*, *41*(6), 983–993. http://doi.org/10.1016/S0896-6273(04)00107-2

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. http://doi.org/10.1080/00335558008248231

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, *109*(2), 160–174. http://doi.org/10.1037/0096-3445.109.2.160

Praamstra, P., Dimitrios, K., Kwok, H. F., & Oostenveld, R. (2006). Neurophysiology of Implicit Timing in Serial Choice Reaction-Time Performance. *Journal of Neuroscience*, *26*(20),

5448–5455. http://doi.org/10.1523/JNEUROSCI.0440-06.2006
Priftis, K., Zorzi, M., Meneghello, F., Marenzi, R., & Umiltà, C. (2006). Explicit versus Implicit Processing of Representational Space in Neglect: Dissociations in Accessing the Mental Number Line. *Journal of Cognitive Neuroscience*, *18*(4), 680–688. http://doi.org/10.1162/jocn.2006.18.4.680
Proctor, R. W., & Cho, Y. S. (2006). Polarity correspondence: A general principle for performance of speeded binary classification tasks. *Psychological Bulletin*, *132*(3), 416–442. http://doi.org/10.1037/0033-2909.132.3.416
Rak, R. J., Kołodziej, M., & Majkowski, A. (2012). Brain-Computer Interface as measurement and control system the review paper. *Metrol. Meas. Syst*, *XIX*(3), 427–444. http://doi.org/10.2478/v10178-012-0037-4
Ramoser, H., Müller-Gerking, J., & Pfurtscheller, G. (2000). Optimal spatial filtering of single trial EEG during imagined hand movement. *IEEE Transactions on Rehabilitation Engineering*, *8*(4), 441–446. http://doi.org/10.1109/86.895946
Ranzini, M., Dehaene, S., Piazza, M., & Hubbard, E. M. (2009). Neural mechanisms of attentional shifts due to irrelevant spatial and numerical cues. *Neuropsychologia*, *47*(12), 2615–24. http://doi.org/10.1016/j.neuropsychologia.2009.05.011
Raymond, J., Shapiro, K., & Arnell, K. (1992). Temporary suppression of visual processing in an RSVP task: an attentional blink? *Journal of Experimental Psychology. Human Perception and Performance*, *18*(3), 849–860.
Regan, D. (1989). *Human brain electrophysiology: Evoked potentials and evoked magnetic fields in science and medicine* (Vol. 1). New York: Elsevier.
Remington, R. W., Johnston, J. C., & Yantis, S. (1992). Involuntary attentional capture by abrupt onsets. *Perception & Psychophysics*, *51*(3), 279–290. http://doi.org/10.3758/BF03212254
Renoult, L., Roux, S., & Riehle, A. (2006). Time is a rubberband: Neuronal activity in monkey motor cortex in relation to time estimation. *European Journal of Neuroscience*, *23*(11), 3098–3108. http://doi.org/10.1111/j.1460-9568.2006.04824.x
Restle, F. (1970). Speed of adding and comparing numbers. *Journal of Experimental Psychology*, *83*(2, Pt.1), 274–278. http://doi.org/10.1037/h0028573
Ridderinkhof, K. R., Ullsperger, M., Crone, E. A., & Nieuwenhuis, S. (2004). The Role of the Medial Frontal Cortex in Cognitive Control. *Science. Special Issue: Cognition and Behavior*, *306*(5695), 443–447.
Ristic, J., Wright, A., & Kingstone, A. (2006). The number line effect reflects top-down control. *Psychonomic Bulletin & Review*, *13*(5), 862–868. http://doi.org/10.3758/BF03194010
Rivet, B., Souloumiac, A., Attina, V., & Gibert, G. (2009). xDAWN Algorithm to Enhance Evoked Potentials: Application to Brain-Computer Interface. *IEEE Transactions on Biomedical Engineering*, *56*(8), 2035–2043. http://doi.org/10.1109/TBME.2009.2012869
Rochester, L., Hetherington, V., Jones, D., Nieuwboer, A., Willems, A. M., Kwakkel, G., & Van Wegen, E. (2005). The effect of external rhythmic cues (auditory and visual) on walking during a functional task in homes of people with Parkinson's disease. *Archives of Physical Medicine and Rehabilitation*, *86*(5), 999–1006. http://doi.org/10.1016/j.apmr.2004.10.040
Rohenkohl, G., Coull, J. T., & Nobre, A. C. (2011). Behavioural dissociation between exogenous and endogenous temporal orienting of attention. *PLoS ONE*, *6*(1), 1–5. http://doi.org/10.1371/journal.pone.0014620
Rohenkohl, G., Cravo, A. M., Wyart, V., & Nobre, A. C. (2012). Temporal Expectation Improves the Quality of Sensory Information. *Journal of Neuroscience*, *32*(24), 8424–

8428. http://doi.org/10.1523/JNEUROSCI.0804-12.2012
Rohenkohl, G., Gould, I. C., Pessoa, J., & Nobre, A. C. (2014). Combining spatial and temporal expectations to improve visual perception. *Journal of Vision*, *14*(4), 1–13. http://doi.org/10.1167/14.4.8
Rohenkohl, G., & Nobre, A. C. (2011). Alpha oscillations related to anticipatory attention follow temporal expectations. *The Journal of Neuroscience*, *31*(40), 14076–14084. http://doi.org/10.1523/JNEUROSCI.3387-11.2011
Rolke, B., Festl, F., & Seibold, V. C. (2016). Toward the influence of temporal attention on the selection of targets in a visual search task: An ERP study. *Psychophysiology*, *53*(11), 1690–1701. http://doi.org/10.1111/psyp.12734
Ryan, D. B., Frye, G. E., Townsend, G., Berry, D. R., Mesa-G., S., Gates, N. A., & Sellers, E. W. (2011). Predictive spelling with a P300-based Brain-computer interface: Increasing the rate of communication. *International Journal of Hum Comput Interact*, *27*(1), 69–84. http://doi.org/10.1080/10447318.2011.535754.Predictive
Salillas, E., El Yagoubi, R., & Semenza, C. (2008). Sensory and cognitive processes of shifts of spatial attention induced by numbers: an ERP study. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *44*(4), 406–13. http://doi.org/10.1016/j.cortex.2007.08.006
Samizo, E., Yoshikawa, T., & Furuhashi, T. (2012). Improvement of spelling speed in P300 speller using transition probability of letters. In *6th International Conference on Soft Computing and Intelligent Systems, and 13th International Symposium on Advanced Intelligence Systems, SCIS/ISIS* (pp. 163–166). Kobe, Japan. http://doi.org/10.1109/SCIS-ISIS.2012.6505350
Sanders, L. D., & Astheimer, L. B. (2008). Temporally selective attention modulates early perceptual processing: Event-related potential evidence. *Perception & Psychophysics*, *70*(4), 732–742. http://doi.org/10.3758/PP.70.4.732
Sandrini, M., & Rusconi, E. (2009). A brain for numbers. *Cortex*, *45*(7), 796–803. http://doi.org/10.1016/j.cortex.2008.09.002
Santens, S., & Gevers, W. (2008). The SNARC effect does not imply a mental number line. *Cognition*, *108*(1), 263–270. http://doi.org/10.1016/j.cognition.2008.01.002
Saupe, K., Schröger, E., Andersen, S. K., & Müller, M. M. (2009). Neural mechanisms of intermodal sustained selective attention with concurrently presented auditory and visual stimuli. *Frontiers in Human Neuroscience*, *3*, 58. http://doi.org/10.3389/neuro.09.058.2009
Schaeff, S., Treder, M. S., Venthur, B., & Blankertz, B. (2012). Exploring motion VEPs for gaze-independent communication. *Journal of Neural Engineering*, *9*(4). http://doi.org/10.1088/1741-2560/9/4/045006
Schroeder, C. E., & Lakatos, P. (2010). Low-frequency neuronal oscillations as instruments of sensory selection. *Trends Neurosci*, *32*(1), 9–18. http://doi.org/10.1016/j.tins.2008.09.012
Schuller, A. M., Hoffmann, D., Goffaux, V., & Schiltz, C. (2015). Shifts of spatial attention cued by irrelevant numbers: Electrophysiological evidence from a target discrimination task. *Journal of Cognitive Psychology*, *27*(4), 442–458. http://doi.org/10.1080/20445911.2014.946419
Schwarz, W., & Heinze, H. J. (1998). On the interaction of numerical and size information in digit comparison: A behavioral and event-related potential study. *Neuropsychologia*, *36*(11), 1167–1179. http://doi.org/10.1016/S0028-3932(98)00001-3
Schwarz, W., & Keus, I. M. (2004). Moving the eyes along the mental number line: Comparing SNARC effects with saccadic and manual responses. *Perception & Psychophysics*, *66*(4), 651–664. http://doi.org/10.3758/BF03194909

Schwarz, W., & Müller, D. (2006). Spatial associations in number-related tasks: A comparison of manual and pedal responses. *Experimental Psychology*, *53*(1), 4–15. http://doi.org/10.1027/1618-3169.53.1.4

Segers, H., Combaz, A., Manyakov, N. V., Chumerin, N., Vanderperren, K., Huffel, S. Van, & Van Hulle, M. M. (2011). Steady State Visual Evoked Potential (SSVEP) - based brain spelling system with synchronous and asynchronous typing modes. In M. Ø. J. K. Dremstrup, S. Rees (Ed.), *In 15th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics (NBC 2011)* (pp. 164–167). Aalborg, Denmark: Springer. Retrieved from www.springerlink.com

Seibold, V. C., Fiedler, A., & Rolke, B. (2011). Temporal attention shortens perceptual latency: A temporal prior entry effect. *Psychophysiology*, *48*(5), 708–717. http://doi.org/10.1111/j.1469-8986.2010.01135.x

Seibold, V. C., & Rolke, B. (2014). Does temporal preparation speed up visual processing? Evidence from the N2pc. *Psychophysiology*, *51*(6), 529–538. http://doi.org/10.1111/psyp.12196

Sellers, E. W., Vaughan, T. M., & Wolpaw, J. R. (2010). A Brain-Computer Interface for long-term independent home use. *Amyotrophic Lateral Sclerosis : Official Publication of the World Federation of Neurology Research Group on Motor Neuron Diseases*, *11*(5), 449–55. http://doi.org/10.3109/17482961003777470

Senkowski, D., Saint-Amour, D., Gruber, T., & Foxe, J. J. (2008). Look who's talking: The deployment of visuo-spatial attention during multisensory speech processing under noisy environmental conditions. *NeuroImage*, *43*(2), 379–387. http://doi.org/10.1016/j.neuroimage.2008.06.046

Serbedzija, N. (2010). Reflective assistance for eldercare environments. In *Proceedings of the 2010 ICSE Workshop on Software Engineering in Health Care (SEHC '10)* (pp. 104–110). Cape Town, South Africa: ACM Press. http://doi.org/10.1145/1809085.1809099

Shaki, S., Fischer, M. H., & Göbel, S. M. (2012). Direction counts: A comparative study of spatially directional counting biases in cultures with different reading directions. *Journal of Experimental Child Psychology*, *112*(2), 275–281. http://doi.org/10.1016/j.jecp.2011.12.005

Silberstein, R., Line, P., Pipingas, A., Copolov, D., & Harris, P. (2000). Steady-state visually evoked potential topography during the continuous performance task in normal controls and schizophrenia. *Clinical Neurophysiology*, *111*(5), 850–857. http://doi.org/10.1016/S1388-2457(99)00324-7

Silberstein, R., Schier, M., Pipingas, A., Ciorciari, J., Wood, S. R., & Simpson, D. G. (1990). Steady-state visually evoked potential topography associated with a visual vigilance task. *Brain Topography*, *3*(2), 337–47. http://doi.org/10.1007/BF01135443

Simon, O., Mangin, J. F., Cohen, L., Le Bihan, D., & Dehaene, S. (2002). Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. *Neuron*, *33*(3), 475–487. http://doi.org/10.1016/S0896-6273(02)00575-5

Snyder, J. S., & Large, E. W. (2005). Gamma-band activity reflects the metric structure of rhythmic tone sequences. *Cognitive Brain Research*, *24*(1), 117–126. http://doi.org/10.1016/j.cogbrainres.2004.12.014

Spaak, E., de Lange, F. loris P., & Jensen, O. (2014). Local entrainment of α oscillations by visual stimuli causes cyclic modulation of perception. *The Journal of Neuroscience*, *34*(10), 3536–44. http://doi.org/10.1523/JNEUROSCI.4385-13.2014

Speier, W., Arnold, C., Lu, J., Taira, R. K., & Pouratian, N. (2012). Natural language processing with dynamic classification improves P300 speller accuracy and bit rate. *Journal of Neural Engineering*, *9*(1), 16004. http://doi.org/10.1088/1741-2560/9/1/016004

Spüler, M., Rosenstiel, W., & Bogdan, M. (2012a). One Class SVM and Canonical Correlation

Analysis increase performance in a c-VEP based Brain-Computer Interface (BCI). In *European Symposium on Artificial Neural Networks, Computational Intelligence and Machine Learning* (pp. 25–27). http://doi.org/10.13140/2.1.2186.7526

Spüler, M., Rosenstiel, W., & Bogdan, M. (2012b). Online Adaptation of a c-VEP Brain-Computer Interface(BCI) based on error-related potentials and unsupervised learning. *PLoS ONE*, *7*(12). http://doi.org/10.1371/journal.pone.0051077

Srinivasan, R., Bibi, F. A., & Nunez, P. L. (2006). Steady-state visual evoked potentials: Distributed local sources and wave-like dynamics are sensitive to flicker frequency. *Brain Topography*, *18*(3), 167–187. http://doi.org/10.1007/s10548-006-0267-4

Sutter, E. (1984). The visual evoked response as a communication channel. In *Proceedings of the IEEE Symposium on Biosensors* (p. 583-). Trans. Biomed.

Suzuki, S. (2001). Attention-dependent brief adaptation to contour orientation: A high-level aftereffect for convexity? *Vision Research*, *41*(28), 3883–3902. http://doi.org/10.1016/S0042-6989(01)00249-8

Suzuki, S. (2003). Attentional selection of overlapped shapes: A study using brief shape aftereffects. *Vision Research*, *43*(5), 549–561. http://doi.org/10.1016/S0042-6989(02)00683-1

Tagliati, M., Bodis-Wollner, I., & Yahr, M. D. (1996). The pattern electroretinogram in Parkinson's disease reveals lack of retinal spatial tuning. *Electroencephalography and Clinical Neurophysiology*, *100*(1), 1–11. http://doi.org/10.1016/0168-5597(95)00169-7

Tallon-Baudry, C., Bertrand, O., Delpuech, C., & Pernier, J. (1996). Stimulus specificity of phase-locked and non-phase-locked 40 Hz visual responses in human. *The Journal of Neuroscience*, *16*(13), 4240–9. http://doi.org/10.1016/j.neuropsychologia.2011.02.038

Talsma, D., Doty, T., Strowd, R., & Woldorff, M. (2006). Attentional capacity for processing concurrent stimuli is larger across sensory modalities than within a modality. *Psychophysiology*, *43*(6), 541–549. http://doi.org/10.1111/j.1469-8986.2006.00452.x

Thut, G., Nietzel, A., Brandt, S. A., & Pascual-Leone, A. (2006). Alpha-band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *The Journal of Neuroscience*, *26*(37), 9494–9502. http://doi.org/10.1523/JNEUROSCI.0875-06.2006

Tipples, J. (2002). Eye gaze is not unique: Automatic orienting in response to uninformative arrows. *Psychonomic Bulletin and Review*, *9*(2), 314–318. http://doi.org/10.3758/BF03196287

Toffanin, P., de Jong, R., Johnson, A., & Martens, S. (2009). Using frequency tagging to quantify attentional deployment in a visual divided attention task. *International Journal of Psychophysiology*, *72*(3), 289–298. http://doi.org/10.1016/j.ijpsycho.2009.01.006

Tonet, O., Marinelli, M., Citi, L., Rossini, P. M., Rossini, L., Megali, G., & Dario, P. (2008). Defining brain-machine interface applications by matching interface performance with device requirements. *Journal of Neuroscience Methods*, *167*(1), 91–104. http://doi.org/10.1016/j.jneumeth.2007.03.015

Townsend, G., LaPallo, B. K., Boulay, C. B., Krusienski, D. J., Frye, G. E., Hauser, C. K., … Sellers, E. . W. (2010). A novel P300-based brain-computer interface stimulus presentation paradigm: moving beyond rows and columns. *Clinical Neurophysiology*, *121*(7), 1109–20. http://doi.org/10.1016/j.clinph.2010.01.030

Treder, M. S., & Blankertz, B. (2010). (C)overt attention and visual speller design in an ERP-Based Brain-Computer Interface. *Behavioral and Brain Functions : BBF*, *6*, 28. http://doi.org/10.1186/1744-9081-6-28

van Dijck, J. P., Abrahamse, E. L., Acar, F., Ketels, B., & Fias, W. (2014). A working memory

account of the interaction between numbers and spatial attention. *Quarterly Journal of Experimental Psychology*, *67*(8), 1500–1513. http://doi.org/10.1080/17470218.2014.903984
van Dijk, H., Schoffelen, J.-M., Oostenveld, R., & Jensen, O. (2008). Prestimulus oscillatory activity in the alpha band predicts visual discrimination ability. *The Journal of Neuroscience*, *28*(8), 1816–23. http://doi.org/10.1523/JNEUROSCI.1853-07.2008
van Ede, F., de Lange, F. P., Jensen, O., & Maris, E. (2011). Orienting attention to an upcoming tactile event involves a spatially and temporally specific modulation of sensorimotor alpha- and beta-band oscillations. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *31*(6), 2016–2024. http://doi.org/10.1523/JNEUROSCI.5630-10.2011
van Galen, M. S., & Reitsma, P. (2008). Developing access to number magnitude: A study of the SNARC effect in 7- to 9-year-olds. *Journal of Experimental Child Psychology*, *101*(2), 99–113. http://doi.org/10.1016/j.jecp.2008.05.001
van Gerven, M., Farquhar, J., Schaefer, R., Vlek, R., Geuze, J., Nijholt, A., … Desain, P. (2009). The Brain-Computer Interface cycle. *Journal of Neural Engineering*, *6*(4), 1–6. http://doi.org/10.1088/1741-2560/6/4/041001
Vanegas, M. I., Blangero, A., & Kelly, S. (2013). Exploiting individual primary visual cortex geometry to boost steady state visual evoked potentials. *Journal of Neural Engineering*, *10*(3), 997–1003. http://doi.org/10.1088/1741-2560/10/3/036003
Vangkilde, S., Coull, J. T., & Bundesen, C. (2012). Great expectations: Temporal expectation modulates perceptual processing speed. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(5), 1183–1191. http://doi.org/10.1037/a0026343
Vangkilde, S., Petersen, A., & Bundesen, C. (2013). Temporal expectancy in the context of a theory of visual attention. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *368*(1628), 20130054. http://doi.org/10.1098/rstb.2013.0054
VanRullen, R., Carlson, T., & Cavanagh, P. (2007). The blinking spotlight of attention. *Proceedings of the National Academy of Sciences*, *104*(49), 19204–19209. http://doi.org/https://10.1073/pnas.0707316104
Venkatagiri, H. S. (1994). Effect of window size on rate of communication in a lexical prediction AAC System. *AAC Augmentative and Alternative Communication*, *10*(June), 105–112.
Vialatte, F.-B. B., Maurice, M., Dauwels, J., & Cichocki, A. (2010). Steady-state visually evoked potentials: focus on essential paradigms and future perspectives. *Progress in Neurobiology*, *90*(4), 418–38. http://doi.org/10.1016/j.pneurobio.2009.11.005
Vidal, J. (1973). Toward direct Brain-Computer communication. *Annual Reviews*, *2*, 157–180. http://doi.org/10.1146/annurev.bb.02.060173.001105
Vogel, S. E., Grabner, R. H., Schneider, M., Siegler, R. S., & Ansari, D. (2013). Overlapping and distinct brain regions involved in estimating the spatial position of numerical and non-numerical magnitudes: An fMRI study. *Neuropsychologia*, *51*(5), 979–989. http://doi.org/10.1016/j.neuropsychologia.2013.02.001
Volosyak, I. (2011). SSVEP-based Bremen-BCI interface - Boosting information transfer rates. *Journal of Neural Engineering*, *8*(3), 1–11. http://doi.org/10.1088/1741-2560/8/3/036020
Volosyak, I., Cecotti, H., & Gräser, A. (2009). Impact of frequency selection on LCD screens for SSVEP based Brain-Computer Interfaces. In IWANN (Ed.), *In LNCS: Bio-Inspired Systems: Computational and Ambient Intelligence* (pp. 706–713). Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-642-02478-8_88
Volosyak, I., Cecotti, H., Valbuena, D., & Gräser, A. (2009). Evaluation of the Bremen SSVEP

based BCI in real world conditions. In *11th International Conference on Rehabilitation Robotics* (pp. 322–331). Kyoto, Japan. http://doi.org/10.1109/ICORR.2009.5209543

Volosyak, I., Moor, A., & Gräser, A. (2011). A dictionary-driven SSVEP speller with a modified graphical yser interface. In J. G. Cabestany Joan, Rojas Ignacio (Ed.), *Proceedings of the 11th international conference on Artificial Neural Networks Conference on Advances in Computational intelligence , IWANN (LNCS)* (pp. 353–361). Torremolinos-Malaga, Spain: Springer-Verlag. Retrieved from http://www.springerlink.com/index/1X776T5621R57307.pdf

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7*(11), 483–488. http://doi.org/10.1016/j.tics.2003.09.002

Walter, S., Quigley, C., Andersen, S. K., & Müller, M. M. (2012). Effects of overt and covert attention on the steady-state visual evoked potential. *Neuroscience Letters*, *519*(1), 37–41. http://doi.org/10.1016/j.neulet.2012.05.011

Wang, Y., Wang, R., Gao, X., & Hong, B. (2006). A Practical VEP-Based Brain – Computer Interface. *Rehabilitation*, *14*(2), 234–240. http://doi.org/10.1109/TNSRE.2006.875576

Wang, Y., Wang, Y. T., & Jung, T. P. (2010). Visual stimulus design for high-rate SSVEP BCI. *Electronics Letters*, *46*(15), 1057. http://doi.org/10.1049/el.2010.0923

Ward, D. J., Blackwell, A. F., & MacKay, D. J. C. (2000). Dasher - A data entry interface using continuous gestures and language models. In *Proceedings of the 13th annual ACM symposium on User interface software and technology* (Vol. 2, pp. 129–137). San Diego, CA. http://doi.org/10.1145/354401.354427

Warm, J. S., Dember, W. N., & Hancock, P. A. (1996). Vigilance and workload in automated systems. *Automation and Human Performance: THeory and Applications*, (July), 183–200.

Weis, T., Estner, B., Krick, C. M., Reith, W., & Lachmann, T. (2015). SNARC meets SPARC in fMRI-Interdependence of compatibility effects depends on semantic content. *Neuropsychologia*, *77*, 331–338. http://doi.org/10.1016/j.neuropsychologia.2015.09.018

Weis, T., Estner, B., van Leeuwen, C., & Lachmann, T. (2016). SNARC (spatial–numerical association of response codes) meets SPARC (spatial–pitch association of response codes): Automaticity and interdependency in compatibility effects. *The Quarterly Journal of Experimental Psychology*, *69*(7), 1366–1383. http://doi.org/10.1080/17470218.2015.1082142

Weiskopf, N., Mathiak, K., Bock, S. W., Scharnowski, F., Veit, R., Grodd, W., … Birbaumer, N. (2004). Principles of a Brain-Computer Interface (BCI) based on real-time functional Magnetic Resonance Imaging (fMRI). *IEEE Transactions on Biomedical Engineering*, *51*(6), 966–970. http://doi.org/10.1109/TBME.2004.827063

Westheimer, G., & Ley, E. (1996). Temporal uncertainty effects on orientation discrimination and stereoscopic thresholds. *Journal of the Optical Society of America A*, *13*(4), 884. http://doi.org/10.1364/JOSAA.13.000884

Wieser, M. J., & Keil, A. (2011). Temporal trade-off effects in sustained attention: Dynamics in visual cortex predict the target detection performance during distraction. *The Journal of Neuroscience*, *31*(21), 7784–7790. http://doi.org/10.1523/JNEUROSCI.5632-10.2011

Wills, S. A., & MacKay, D. J. C. (2006). DASHER - An efficient writing system for Brain-Computer Interfaces? *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *14*(2), 244–246. http://doi.org/10.1109/TNSRE.2006.875573

Wolfe, J. (2014). Theoretical and behavioral sspects of selective attention. In M. s. Gazzaniga & G. R. Mangun (Eds.), *The Cognitive Neurosciences* (fifth Edit). London, UK: The MIT

Press.
Wolpaw, J. R. (2007). Brain-Computer Interfaces as new brain output pathways. *The Journal of Physiology*, *579*(Pt 3), 613–619. http://doi.org/10.1113/jphysiol.2006.125948
Wolpaw, J. R., Birbaumer, N., Heetderks, W. J., McFarland, D. J., Peckham, P. . H., Schalk, G., … Vaughan, T. M. (2000). Brain-Computer Interface technology: A review of the first international meeting. *IEEE Transactions on Rehabilitation Engineering*, *8*(2), 164–173. http://doi.org/10.1109/TRE.2000.847807
Wolpaw, J. R., Birbaumer, N., McFarland, D. J., Pfurtscheller, G., & Vaughan, T. M. (2002). Brain-computer interfaces for communication and control. *Clinical Neurophysiology*, *113*(6), 767–791. http://doi.org/10.1016/S1388-2457(02)00057-3
Wood, G., Willmes, K., Nuerk, H.-C., & Fischer, M. H. (2008). On the cognitive link between space and number: a meta-analysis of the SNARC effect. *Psychology Science Quarterly*, *4*(4), 489–525. http://doi.org/10.1027/1618-3169.52.3.187
Woodrow, H. (1914). The measurement of attention. *Psychological Monographs*, *17*(76), 1–158. http://doi.org/10.1017/S136064179800149X
Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(1), 95–107. http://doi.org/10.1037/0096-1523.20.1.95
Yeshurun, Y., Montagna, B., & Carrasco, M. (2008). On the flexibility of sustained attention and its effects on a texture segmentation task. *Vision Research*, *48*(1), 80–95. http://doi.org/10.1016/j.visres.2007.10.015
Yi, W., Qiu, S., Qi, H., Zhang, L., Wan, B., & Ming, D. (2013). EEG feature comparison and classification of simple and compound limb motor imagery. *Journal of NeuroEngineering and Rehabilitation*, *10*(1), 1. http://doi.org/10.1186/1743-0003-10-106
Ying, J., Sherry, L., & Hui, Y. (2011). *Think and type: Decoding EEG signals for a Brain-Computer Interface virtual speller*. *ssrc.wiki.hci.edu.sg*. Singapore. Retrieved from http://ssrc.wiki.hci.edu.sg/file/view/SSEF+2012+CS008_Report.pdf/333296132/SSEF 2012 CS008_Report.pdf
Yu, X., Chum, P., & Sim, K. B. (2014). Analysis the effect of PCA for feature reduction in non-stationary EEG based motor imagery of BCI system. *Optik*, *125*(3), 1498–1502. http://doi.org/10.1016/j.ijleo.2013.09.013
Zahn, T. P., & Rosenthal, D. (1966). Simple reaction time as a function of the relative freqeuncy of the preparatory interval. *Journal of Experimental Psychology*, *72*(1), 15–19.
Zanolie, K., & Pecher, D. (2014). Number-induced shifts in spatial attention: A replication study. *Frontiers in Psychology*, *5*(AUG), 1–10. http://doi.org/10.3389/fpsyg.2014.00987
Zanto, T., Hennigan, K., Mattias, O., Clapp, W., & Gazzaley, A. (2010). Predictive knowledge of stimulus relevance does not influence top-down suppression of irrelevant information in older adults. *Cortex*, *46*, 564–574. http://doi.org/10.1016/j.cortex.2009.08.003
Zanto, T., Pan, P., Liu, H., Bollinger, J., Nobre, A. C., & Gazzaley, A. (2011). Age-related changes in orienting attention in time. *J Neurosci*, *31*(35), 12461–12470. http://doi.org/10.1523/JNEUROSCI.1149-11.2011
Zhang, Y., Zhou, G., Zhao, Q., Jin, J., Wang, X., & Cichocki, A. (2013). Spatial-temporal discriminant analysis for ERP-based Brain-Computer Interface. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *21*(2), 233–243. http://doi.org/10.1109/TNSRE.2013.2243471
Zohar-shai, B., Tzelgov, J., Karni, A., Rubinsten, O., Zohar-shai, B., & Tzelgov, J. (2017). It Does

Exist ! A Left-to-Right Spatial – Numerical Association of Response Codes (SNARC) Effect Among Native Hebrew Speakers. *Journal of Experimental Psychology : Human Perception and Performance*, *43*(4), 719–728. http://doi.org/10.1037/xhp0000336
Zorzi, M., Priftis, K., & Umiltà, C. (2002). Brain damage: Neglect disrupts the mental number line. *Nature*, *417*(6885), 138–139. http://doi.org/10.1038/417138a

ACKNOWLEDGEMENTS

It is a dream came true being writing the last section of my doctoral thesis, and here I am thanks to Mike, Richard and Marc. And it all started when Marc accepted to supervise my master thesis, thanks Marc for your support from the beginning and for inviting me to be part of your research group, it has been a wonderful experience to meet all the great people in your group in Leuven. Some of them were next to me as kind colleagues and some others also as friends, and because of them I could enjoy my PhD life from different and interesting points of view, so thanks Kolya, Dr. Nick, Adrien, Yelena, Elvira, Flavio and Marie-Eve for the good moments, knowledge, fun and academic experiences, for your support and for your friendship during my time in Belgium.

Probably one of the most important conferences I've ever attended to was the SRP meeting 2013 in Florence where I heard for the first time Mike's time frequency analysis talk. That talk changed the course of my PhD and my academic life. Thanks Mike for accepting my invitation to be my co-supervisor, for teaching me so many things in these three years, for sharing your knowledge, for your patience to explain and to teach me about Matlab, methods and data analysis; for all the challenges, and the courses that lead me to learn more and more every day. And thanks for all the brief non-scientific talks we had along this time, from them I learnt a lot about you as the brilliant scientist you are and also the great human being behind all the science ☺. And also, I want to thank Richard for accepting to be my supervisor and helping me with the joint program together with Mike so I could stay and work here at the UvA. Thanks Richard for believing in me, for always providing different perspectives and solutions about the research or personal life, and thanks for the coffee and beer talks, it was easier to deal with some academic and non-academic issues every time I came to you, you always had time and a good advise.

Special thanks to Helen Slagter, Birte Forstmamm, Cees van Leuven, Maurits van der Molen, Filip van Opstal, Walter Schaeken and Joan Duprez for the time to read and evaluating my thesis manuscript, and particularly for those traveling all the way from Belgium and France to attend to my ceremony.

To my paranymphs Leon and Julian, thanks for being my colleagues and friends and specially for being, literally, next to me on my defense, I couldn't have better paranymphs than you guys.

Gracias a Samilo quien siempre estuvo ahí, e incluso desde mucho antes. Tu compañía, y tu fortaleza fueron fundamentales para mí, siempre fuiste el apoyo y la sonrisa en los momentos difíciles así como la alegría y celebración en las pequeñas victorias, gracias por tu presencia y por haber recorrido tan importante parte de este camino junto a mi Samilo. Also, it has been the support of many people during my time in The Netherlands and at the UvA that made everything easier, funnier and more interesting to live. Thanks to Renate and Don Juan for the dinners, drinks, New Years Eve and the nice moments we have shared within and outside the UvA. To Leon who always had time to help me out or explaining whatever I asked, you are definitely one of the nicest guys I've ever met!! Thanks for all your help and for *hired* me as your teaching assistant :-p.

One of the nicest memories I have are from the time in Glasgow where you guys, Josipa, Noor and Lukas were so kind and nice taking care of me due to my "temporal disability", it was amazing and you made me feel so great, thank you so much!!

Thanks to Yair for the sportive days and Valentines' day celebrations…hehehe…A Esperanza por las conversaciones en Español que nos permitian romper la rutina del día a día con algo de cotilleo. To Dr. van Gaal for the informal and sometimes very formal talks while sharing a coffee or a beer. To Steven for his support so I could attend to my last NVP meeting. To Jaap who never had a no as an answer when I needed to extend my time as a research guest at the Brain and Cognition.

Y cuando de paseos e irresponsabilidad se trata, no pude contar con mejor mentor que el Sr. Dr. Bonilla! Gracias gordo por los viajes y los momentos compartidos :p, por los años de incondicional amistad y desde luego por aceptar acompañarme el día de mi defensa!

I had amazing and funny moments during the lunch breaks, the beers in Kriterion and CREA and from all the times we gathered out of the department. And of course I had the opportunity to learn a lot through the scientific discussions in the journal clubs, BCM (formerly BBM), lunch breaks, drinks in the department ... the people were always willing to share their knowledge, to discuss or to make suggestions about any topic I were struggling with. Thanks a lot to the current and some former B&C members for all these great moments: Marlies, Lotte, Leon, Lukas, Josipa, Max, Ilja, Olympia, Thomas, Noor, Martine, Marte, Anne, Jan-Willem, Lucia, Valeria, Timo, Camile, Lynn, Heleen F., Matthew, Dirk, Lola, Daniel, Tim, Hilde, Manon, Simon, Steven, Zai-Fu, Jim, Niels, Fleur, Esperanza, Romke, Jessika, Stijn and Evert.

Hubert and Ingrid, you were always very helpful and had patience to deal with all the administrative issues that came with my joint program, thank you for all your help.

Thanks Valeria for accepting my invitation to be the official photographer of my defense ☺ yeahhh!!!

Desde luego la compañía de los amigos fuera de la U fue vital para disfrutar Amsterdam mientras se vivia un poco la tierrita, gracias a Tierra Mestiza por la aventura folcklórica, en especial a Arnold, Yohana, Angela y Carmenza por los bailes y todo los buenos momentos que vinieron con ellos; a Ruby por acogerme en Alegría y por los buenos momentos, and to John for the nice beers and all the interesting conversations we had.

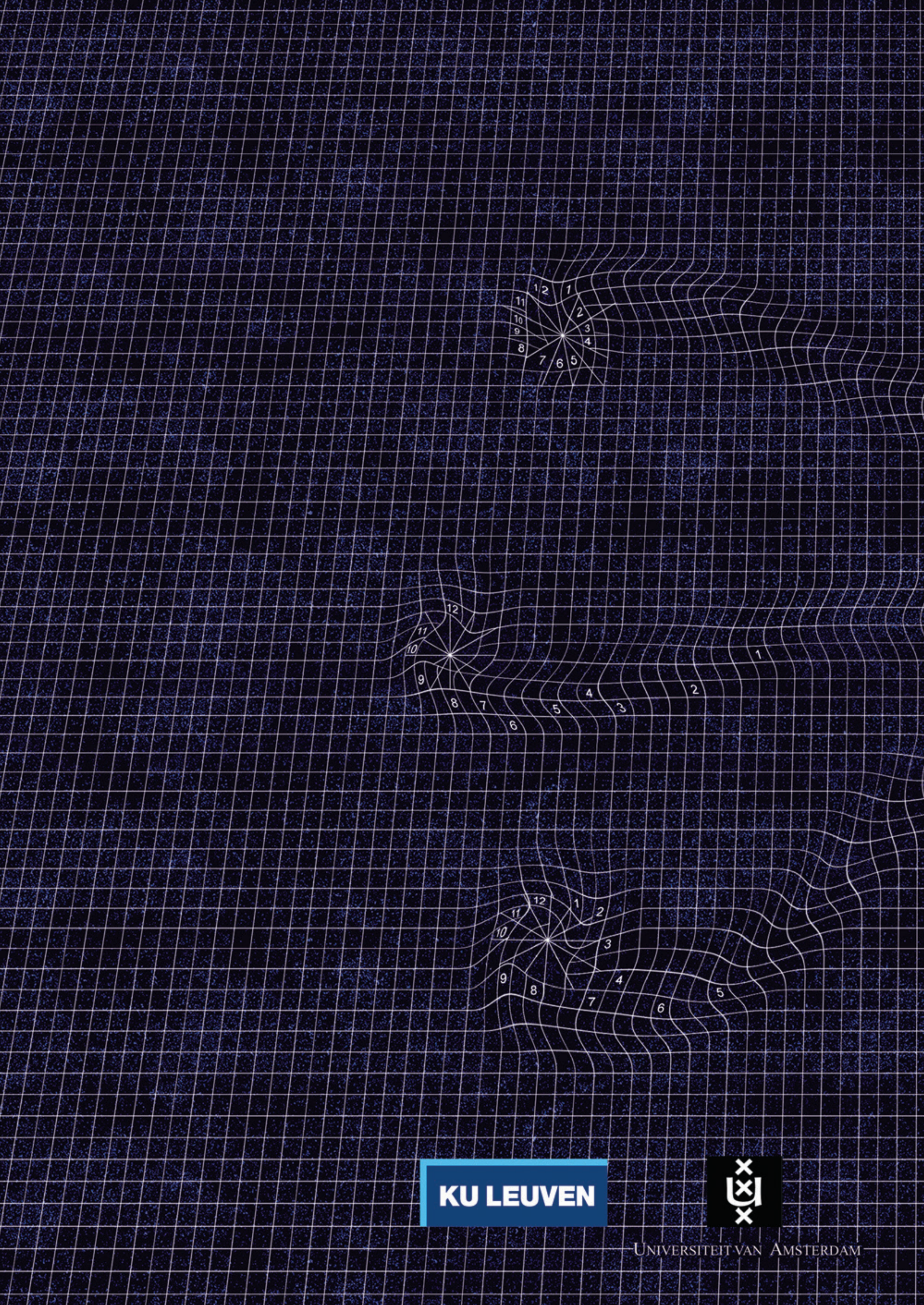
To Alenka and Rastio for the *journey*, advises, nice moments and interesting conversations. Por las conversaciones, cenas y polas que comparti con mis queridas caleñas Angela y Carolina y ellas con este cachaco.

Writing part of my thesis next to the swimming pool in Las Vegas was one of those memorable moments I experienced with my dear Danny and with Anibal, Fabio, Ana and Alex, it was an amazing trip, thank you guys.

Por supuesto, afrontar y disfrutar cada unos de los momentos que se viven en esta etapa no habria sido lo mismo si no hubiese contado con el amor de la familia. Gracias mamita por estar a mi lado día a día, por el ejemplo de transparencia, honestidad y trabajo y porque aún en la distancia sentia el calor de tú amor, tú apoyo en cada momento especial, fortaleciendome en los difiíciles y haciendome sentir aún más feliz en los buenos momentos. Gracias papá por mostrarte todo cuanto los libros pueden enseñarnos y el mundo que se puede descubrir a traves de la lectura, verte leer tantos libros con tanta pasión marco mi deseo de conocimiento desde muy temprano. A mi tío Jose por ser un modelo de crecimiento intellectual, de compromiso, por su voz de aliento y su permantente orientación, siempre ayudandome a tomar la major decisión y camino para mi presente y futuro. A mi tía Margarita quien siempre estuvo presente y por supuesto a las tias Marta y Nelly quienes siempre tuvieron una voz de apoyo a lo largo de este proceso. A mi adorada abuelita Carmen quien siempre me tuvo en el centro de su corazón acompañandome cada día con sus dulces palabras. To Jim for his support, his interesting conversations and for opening the doors of his house making me feel at home during the amazing days I was there, it was really amazing, thanks.

And the lovely support of my dear Danny along the last months (and probably the most intense times of my PhD) made look everything way easier. Your love, support, company and patience when I found myself close to an emotional collapse cooled me down and helped me to go back to the positive side I usually take. In a very short time we have shared

very intense moments including hospitals, ambulances, trips, sun, sea, beaches, old towns in the middle of nowhere and much more, and in all of them your hand was always holding mine no matter what. We found the way to smile and to support each other and continue walking together to the end of the day. Thanks my sweet Daniela for all these beautiful moments between us.



KU LEUVEN

Universiteit van Amsterdam