Driver performance, prediction and brain rhythms: What we can learn from external sensory entrainment?

Rodrigo Henriquez Chaparro[1,2], Francisco J. Parada[1], Franco Basso[3], Leonardo J. Basso[4], Raul Pezoa[4], Francisca Cuevas[3], Diego de la Barra[5], and Daniel Rojas-Líbano[1]

[1]Laboratorio de Neurociencia Cognitiva y Social, Facultad de Psicología, Universidad Diego Portales
[2]Department of Psychiatry, Interdisciplinary Center for Neurosciences, School of Medicine, Pontificia Universidad Católica de Chile, Santiago, Chile
[3]School of Industrial Engineering, Diego Portales University, Santiago, Chile
[4]Civil Engineering Department, Universidad de Chile, Santiago, Chile
[5]Programa de Magíster en Neurociencia Social, Facultad de Psicología. Universidad Diego Portales. Santiago, Chile

September 4, 2018

Abstract

Drive performance in complex road scenarios research usually tends to mainly consider variables as the accuracy of motor human behavior, attentional focus levels, and technological devices for predicting risky events. However, recent evidence -particularly within visual perception research- indicates that the nervous system is continuously coupled with the dynamic, ever-changing environment. This is a highly adaptive feature allowing the online adaptation of the nervous system to the rhythm of incoming stimuli. Evidence-based current ideas about brain functioning suggest that *Bayesian* operations combined with external sensory entrainment approaches might improve human perception performance. These advancements provide a unique opportunity to refine high-performance motor-sensory coupling. Likewise, allowing evidence-based development of innovative strategies for accident prevention and road design. Thus, given the dramatic lifestyle changes and the rapid expansion of cities occurring in the modern globalized world, we provide a new perspective for the establishment of innovative vial infrastructure and accident prediction systems. Importantly, these systems and devices can be designed using behavioral and neural information obtained from human drivers with diverse cognitive, sensory, perceptual, and behavioral characteristics.

Keywords: sensory entrainment, rhythmic stimulation, perception, driving performance, brain rhythms

***Correspondence:** Rodrigo A. Henríquez Ch.

rhenriquezch@gmail.com

Sensory entrainment: Neurobiological underpinnings for accident prevention.

Over the course of the last 30 years, a large body of experimental and theoretical literature has suggested that perception is a discrete phenomenon (VanRullen and Koch, 2003; Friston et al., 2010; Asplund et al., 2014; Thibault et al., 2016; Seth et al., 2008; VanRullen, 2016; Sergent and Dehaene, 2004; Friston, 2005) **(Marti., 2017; Varela et al., 1981**. This is, human perception is based on discrete neural processing cycles rather than a continuous stream of accumulating information. Such processing cycles have been often associated with brain rhythms; short-lived voltage variations observable at the level of microcircuits and large-scale neural networks emerging from the apparently stochastic behavior of individual neurons (Buzsaki, 2006). Such "coordinated" brain activity is frequently associated with rhythmic fluctuations in the excitation–inhibition cycle of local neuronal populations, modulating the global organization of our nervous system **(Herter, 1967; Hirsh & Serrick, 1961; Varela et al., 1981; VanRullen et al., 2011**; (Varela et al., 2001; Quyen, 2011; Quyen and Bragin, 2007) and generating variability in sensory and perceptual processing **(Varela et al., 1981)**. Thus, to form a coherent representation of the world around us, the brain must dynamically organize the different sensory features composing our global perception (Bagdasaryan and Quyen, 2013; Quyen, 2011; Varela et al., 2001; Hasson et al., 2008). The nervous system's ability to continuously couple with dynamic visual inputs depends on the synchronous neural entrainment to the rhythm of incoming stimuli (Spaak et al., 2012; Spaak et al., 2014). Improved perceptual processing and increased behavioral performance can be reached through "optimal" brain rhythm coupling mechanisms (Arnal and Kleinschmidt, 2017; Ronconi and Melcher, 2017; Henry and Obleser, 2012) and in this manner, taking advantage of the entrainment property of endogenous neural oscillations involving sensory processing reorganization. However, practical applications of these new and interesting findings are lacking. Such applications could facilitate the development of novel ecological tools supporting human sensory adaptation in everyday complex environments.

Within this context, automobile driving can be understood as a complex task requiring sensory information processing, visual perception integration, and decision making under conditions of high perceptual uncertainty. In natural driving conditions, a busy road with incoming traffic is a common scenario. Eye fixations will concentrate on the road ahead, while periodically fixating towards the rear-view mirror sets (Nunes and Recarte, 2002). Moreover, covert attention will be deployed towards the incoming traffic and potential pedestrians; shifting between unattended visual fields. Thus, driver performance studies are a well-suited model for studying neural mechanisms allowing the identification and processing of diverse dynamic stimuli.

The fields of Cognitive Psychology and -more recently- Cognitive Neuroscience has produced a variety of research tools composed by experimental and computational techniques. These methodological tools allow the identification and modulation of oscillatory brain activity; having direct impact on sensory, perceptual, and behavioral processes (Wutz et al., 2014; Thut et al., 2011). Likewise, a growing number of studies provide key insights about psychophysiological factors and their impact on driving performance (Mehler et al., 2009; Thiffault and Bergeron, 2003; Lal and Craig, 2001; Klinestiver, 1980). These studies focus on quantifying the impact on driving performance of cellphone calls (Nunes and Recarte, 2002), texting while driving (Caird et al., 2014), conversations with passengers (Drews et al., 2008), spontaneous episodes of breakdown of attentional stream (i.e. mind wandering) (Henríquez et al., 2016; Thomson et al., 2014; Yanko and Spalek, 2014; He et al., 2011), among others factors. Additionally, other human demographical and historical factors such as age and driver accident records are variables that also impact overall driving performance (Horberry et al., 2006; Ball and Owsley, 1993). Thus, growing evidence indicate these distractions are associated with reduction of reaction times, attentional impairments such as "tunnel vision", limiting peripheral vision, and -of course- increasing the overall risk of accidents **(Alexander et al., 2004; Robb et al., 2008;** (Petridou and Moustaki, 2000). Although relevant evidence has been gathered about built environment, human, and cognitive factors predicting automobile accidents, a unifying neurobiological model providing clear empirical hypothesis is still lacking.

In the present perspective article we will highlight the role of perceptual cycles and sensory entrainment processes as an integrative and ecological neurobiological model of driver's cognitive and behavioral performance. Our main hypothesis is that external modulation of visual sensory processing of incoming stimuli, would improve the perception and behavior (i.e: sensory-motor coupling) during automobile driving. If true, our hypothesis suggests the possibility to set a driver's sensory system within a range of "optimal perceptual state", allowing processing external sensory demands successfully. Furthermore, we suggest cognitive neuroscience should work towards establishing a relationship between driving performance and external sensory entrainment of neural oscillations. Establishing such a link would allow the implementation of real-time information delivery systems working alongside innovative probabilistic collision prediction applications indicating collisions and road hazards (Basso et al., 2018). Providing thus a starting point for the development of perceptually-driven interactive vial infrastructure and other empirically-designed applications for car accident prevention.

Brief overview of driving activity and risk management respect to neuroscience

One of the most commonly used models to describe driving activity is the Michon model (Michon, 1985). This approach divides driving behavior into two main classes: *taxonomies* and *functional models.* Taxonomies have the advantage of disturbing and classifying the different components of driving activity, but do not express the dynamics between these components. In turn, functional models, give an idea of the relationship between the elements, but are sometimes too restrictive and do not always go beyond their own field of study. Thus, the cognitive model of automotive activity by Michon is presented in a simple and flexible structure, which can group different hierarchical and theoretical levels (Michon, 1985). The model is further divided into three main parts corresponding to levels of competence in driving activity. The level of *rational operation*, which contains all the necessary actions to control the car. The *tactical level*, which refers to placement and positioning maneuvers in traffic and infrastructure. Finally, the *strategic level* allows planning of driving objectives, route and choice of transportation mode. These different levels influence each other in such a way that driving conditions or the driver's willingness to drive can change in any time. For instance, when a driver interacts with traffic and unexpectedly changes the route. Another example would be taking an exit off a highway, for which our strategic driving can change due to the availability of different options. The driver can make the tactical choice of overtaking, which involves significant speed reduction and lateral positioning of the vehicle at the rational operating level. On the contrary, the driver can also tactically choose not to make a road overtaking, which will facilitate the rational positioning of the vehicle to the next point on the route. The decision between these two options will depend in part on the driver's *risk management* and *perception.* According to the risk homeostasis model (Wilde, 1998), decisions corresponding to the strategic level of the Michon model (Michon, 1985) depend on an optimization of the driver's risk decision making. In fact, the driver would choose the most appropriate manoeuvre based on four dimensions related to the risk homeostasis model: (i) expected benefits and (ii) expected costs of the risk behavior, and (iii) expected benefits and (iv) costs of the safe behavior. According to the risk model, driving always involves some risk. Likewise, there is always a goal to achieve. A driver will have a specific level of risk, deriving maximum benefit associated to the accomplishment of such a goal. The risk threshold would determine is the risk is worth taking in order to achieve a particular goal. Thus, risk taking may be voluntary if the individual decides to perform a maneuver by accepting the risks. In contrast, it can also be involuntary, because the individual could make a decision without knowledge of all the critical elements of the situation (Wilde, 1998). Behaviors related to driving are directly linked with this real world experience. Unfortunately, given the internal/ecological validity trade-off, the majority of experimental laboratory approaches related to the driving activity and its risk management tend to lack ecological validity. These studies, focus on exploring the impact of optimization of sensory processing on decision-making as well as on executive functions [**need citation**]. In this sense, considering more reliable variables that are closer to real world driving behavior, should be a main goal in the design of experimental protocols. Thus developing a more ecological approach to studying the psychobiological correlates of the driving activity. We argue that experimental designs should aim at reproducing the complex and dynamic tasks that people face in their daily lives. It is for this reason that driving should be considered in relation to cognition, behavior, and technological devices in the actual environment where it occurs (Menary, 2013; Gallagher and Crisafi, 2008). Furthermore, the relationship between drivers and cars must be established as a joint cognitive system that functions in real-world settings. Consequently, any interventions aiming at improving and supporting the driving activity should focus on the neural bases of sensory, perceptual and cognitive functions and actions in relation to driving technologies and urban road settings. Providing thus opportunities for translational research between neuroscience, human behaviors variability, engineering, computer science, and public policy and socio-political sciences.

Recent knowledge about neural bases of sensory and cognitive functions underlying driving sheds light on the understanding of human behavior and to improve the performance in a wide range of driving settings [**need citation**]. A key area where neuroscientific interventions can be applied is in the creation of tailored strategies for optimizing perceptual sensory processing as a safety measure in automobile driving designed from and for the human brain. Reaching this goal would require examining sensory and perceptual processes in driving, which tend to be overly demanding on normal driving settings (Lee et al., 2008; Walter et al., 2001; Deery, 1999; Ranney, 1994). According to studies about accident records, the proportion of fatal crashes for drivers on highways is expected to increase due to demographic shifts in the modern cities (McGwin Jr et al., 1998; McGwin Jr and Brown, 1999). Recent findings suggest a 155% increase by 2030, for instance, for drivers aged 65 and above (Lyman et al., 2002). These projections of increased crash risk for different type drivers can arise from age related factors and psychophysical performance associated with sensory, perceptual processing and attentional impairments, among others. These variables can in turn be caused by external factors such as distractions, as well as internal ones, such as a deteriorations in some perceptual modality (e.g. visual or hearing impairments) (Preusser et al., 1998; Owsley et al., 1991; Ball and Owsley, 1993). For this reason, the study of the driving activity demands a multidisciplinary translational approach which must merge elements of cognitive psychology and human factors to study brain structure and function in everyday environments, which are often studied in isolation and so present a challenge in generalizing neurophysiological findings to predict driving safety behavioral actions. In this direction, cognitive neurophysiology can be used to explain and understand the mechanisms for instance of attentional breakdown that might be associated with driving behavior problems. Thus, a more complete picture of the the basic sensory processes that drivers need in the real-world might come from examining their performance in controlled laboratory studies to determine the the basic neurophysiological requirements for perceptual sensory processing to operate effectively and successfully in all driving scenarios. Future research on the driver's performance might further explore the ability of sensory entrainment to modulate the sensory processing systems in order to determine how well the driver can compensate and improve their sensory, perceptual and behavioral ability. Results from these type of efforts might play a role in the reduction of accidents. A physiological perspective and neuroscientific approach to drivers' perceptive skills can be useful to investigate a variety of cognitive states that affect various driving settings.

Linking the Bayesian brain, perceptual uncertainly, and cognitive prediction at the wheel

The nervous system's ability to dynamically coordinate cognitive functions in a world of sensory uncertainty is one of the greatest evolutionarily-given tools (Jensen et al., 2012). Although from experience, our perceptual world looks stable and determined, many factors indicate that coordination with incoming sensory information is less reliable than it appears (Geisler and Kersten, 2002). For example, the variability in the density of the receptors of the retina -as well as the structural limitations in neural organization and the variety and variability of information introduced in the early stages of sensory coding- mean that the nervous system must dynamically and effectively deal with the resulting uncertainty. Appropriate uncertainty management generates accurate perceptual representations of the world. Thus guiding decisions and actions in a more adaptive manner. Therefore, perception is a process of active unconscious and probabilistic inference (Friston et al., 2012; Moutoussis et al., 2014; Moutoussis et al., 2014) (**Barlow 1990 –> no lo encuentro**).

On the one hand, Bayesian methods have proven successful in describing computational theoretical models for perception and sensory-motor control (Buckley et al., 2017). On the other hand, psychophysics has provided a growing body of evidence on how perceptual calculations in human beings follow an optimal Bayesian pattern (Buckley et al., 2017). This means that Bayesian coding approach reverse the notions classically established of perception as a largely bottom-up process of information accumulation or stimulus detection driven by the impact of sensory signals. Suggesting instead that both perceptual content and behavioral response is determined by top-down predictive signals. These signals would arise from multi-level generative internal models of environmental sources, which are continually modified by bottom-up prediction error signals. The latter ones, communicating reciprocal exchanges of information between predicted and actual signals across the different sensory and perceptive hierarchical levels, ultimately impacting on behavioral execution. Thus, evidence indicates the processes by which the human brain represents incoming sensory information, could be understood in a probabilistic way [**CITE EVIDENCE**]. Thus, the *Bayesian coding hypothesis*, suggests the human brain could be a natural probability distribution generator **(Friston., 2009, 2010)**. This theoretical and experimental approach has fundamental implications for studying the brain in everyday environments, particularly in the way we understand and describe the neural calculations and natural dynamics of neural representations. However, direct applications in daily life on this hypothesis are almost non-existent. Determining how and which are the requirements of the driver's brain to coordinate, the dynamics and natural neuronal interactions that are useful for the effectiveness of information coding in environments of high sensory uncertainty, is an important objective not only for the development of neuroergonomics as a field, but also a major advance in the field of applications in complex social contexts.

In consequence, considering the Bayesian brain framework **(Friston, 2009, 2010 & 2011)**, if we provide relevant information to optimize a probability calculation (e.g. the prediction of motor behavior on a highway) our brain would use this information and modify itself from its interaction with incoming stimuli. Thus drawing a probabilistic prediction, with higher success rate of what *could* happen within the given context. In real high-uncertainty road driving conditions, the drivers' brain would consider the inputs from the environment and compare them with their previous experiences, in order to regulate and modify their behavior according to perceived risk (Wilde, 1998). In turn, optimization of brain functioning -by integrating the most relevant variables and trying to zero out any errors in its predictive model- can occur in a moment-by-moment basis. Furthermore, optimization involves updating the current model to reevaluate sensory inputs. Selective sampling of new incoming sensory inputs will thus generate adaptive responses reducing uncertainty and facilitating behavioral performance (Friston and Frith, 2015). Hence the nervous system is prepared to make active and probabilistic inferences of what might happen in our nearby sensory world. Furthermore, it can update such models with new predictive information, increasing the degree of accuracy. Environmental Psychology can therefore use this framework in order to develop systems that can facilitate such an optimization process. For example, using information derived from state-of-the-art predictive model of accidents in order to provide online non intrusive data about driving conditions (Basso et al., 2018). Given the fact that in real driving scenarios signals and stimuli are in constant competition, transmitting information to drivers is not an easily achievable goal.

Brain oscillations, rhythmic stimulation and non-Invasive sensory entrainment

The functional architecture of perception is supported by distinct neurophysiological rhythms organized across different spatial scales (Buzsáki, 2004). This essential function -potentially supporting all cognitive activity- has its basis that start from a single neuron (Hutcheon and Yarom, 2000) passing through different neural circuits (Whittington et al., 1997) to thalamo-cortical and cortico-cortical networks (Lőrincz et al., 2009). Thus, different brain rhythms occur at distinct frequency bands as a function of micro- and macro-network architecture (Buzsáki, 2004). Different aspects of cognitive activity can thus be described in terms of neuronal oscillators, hierarchically organized interacting at different frequencies (Buzsáki, 2004). A biological mechanism named *synchronization of neuronal elements* enables the dynamic perceptual framing of sensory information (Varela 1981); a neurophysiological process derived from oscillatory coordination (Jensen and Mazaheri, 2010; Salinas and Sejnowski, 2001; Fries, 2005). Within this neural mechanism, temporal segmentation serves to reduce the problem of information overload because sensory stimuli can be processed serially. In this context synchronous voltage variations that occurring within 8-13 Hz in adults and within 6-9 Hz in children, known as alpha oscillations are thought to be a crucial element or these processes (Palva and Palva, 2007). Furthermore, these lower frequency rhythms (theta 4-8 Hz, alpha 8-13 Hz) have been related to long-distance brain communication dynamics, while higher frequency bands like gamma (>30 Hz) have been associated with local neuronal interaction (von Stein et al., 2000). It has been proposed that low- and high-frequency oscillatory systems belong to a larger multi-band coordination system, enacting an informational multiplexing mechanism (Akam and Kullmann, 2014) through cross-frequency interactions (Palva and Palva, 2007; Jensen and Colgin, 2007; Canolty and Knight, 2010). Activity in different frequencies across brain structures may also provide important clues to these functions, for instance posterior alpha-band oscillations (8–12 Hz) are related to the sensory input regulation (Lőrincz et al., 2009), and attentional selection (Thut and Miniussi, 2009; Worden et al., 2000; Sauseng et al., 2005; Kelly et al., 2006). Hence, when perception unfolds during driving activities, also relies on processes that enable effective selection and integration of relevant information from the vast amount of sensory inputs on the road, that is constantly bombarding the driver's brain. Sensory function improvements could be therefore made by a natural property of oscillations. This is, oscillatory activity is self-sustained and dynamic (e.g. (Pikovsky et al., 2003; Glass, 2001)), implying that brain rhythms could be modulated by an external sources. For instance, if the modulation is carried out periodically by an external stimulus, the ongoing waves may then become synchronized to the external patterns. In other words, brain rhythms will synchronously cycle with the same period as the external sensory input, becoming "*entrained* " and coordinated to the rhythm of external incoming events (Lakatos et al., 2008). Within this context, *synchronization* and *entrainment* are synonymous (Pikovsky et al., 2003). Thus, in this perspective we will use the term entrainment to refers synchronization to a natural brain rhythmic with rhythm of external (sensory) incoming events.

RE-ESCRIBIR, NO SE ENTIENDE –> [Therefore, generating non-invasive stimulation of a coordinated nature pulsed sensory stimulation appear as key tool for simultaneously entrain many primary sensory structures and input pathways including sub-cortically and cortical structures. In this context pulsed form of rhythmic stimulation is steady-state sensory stimuli presentation.] For instance, transient visual events that are repeated at fixed frequency (Herrmann, 2001), in order to entrain the natural brain frequencies to the rhythm of the presentation. With this non-invasive approach to sensory stimulation, stimuli can be presented in a wide range of repetition frequencies, covering the physiological range of brain oscillations from slow-waves to high-frequencies bands (Herrmann, 2001; Thut and Miniussi, 2009), allowing non-invasive brain stimulation at appropriate frequencies and temporal scales. Likewise, inducing sensory entrainment on drivers' brains appear as a perfect candidate to generate non-invasive safety tools for prevention of automobile accident. In addition, note the possibility of generating a tool in road infrastructure to modify and improve the perceptual and behavioral performance of drivers appears as a neuroergonomic challenge in urban design, as well also opening a new path in the way the concept of road safety is constructed, designed from and for the human brain.

Concluding remarks

Current descriptions of the role of brain oscillations in the execution of complex behavior is a fundamental aspect to understand the role of external sensory modulation to improve the coupling with the world (Varela, 1981; (VanRullen et al., 2005), suggesting a biological-tech support for driving performance. This neurophysiological reinforce can be interpreted in terms of a “optimal temporal window” for establishing the best time to deliver the stimulus (Ronconi and Melcher, 2017; Wutz et al., 2018; VanRullen et al., 2005; VanRullen et al., 2005) Varela 1981, connecting the on coming stimuli with the optimal sensory rhythms. Here, we have proposed that effective sensory entrainment constitutes a novel approach to help perceptual processing during driving performance and explain why we can improve, a least temporality the performance on complex task such driving. Specifically, effective neurophysiological, cognitive, and computing neuroscience studies allow us to hypothesize that the temporal synchrony within a window of visual integration would provide a high temporal resolution, necessary for the stability of perceptual representation, despite the rapid changes in sensory inputs present on complex vial scenarios (Wutz et al., 2014). Thus, improve the anticipatory behaviors before the execution of the desired action (Khaliliardali et al., 2012). Therefore, these are the aspects that must be considered in order to improve the chances of attending for instance to preventive signs within the road environment. Moreover, given the existence of multi sourcing of sensory stimulus processing deficits that affecting the cognitive domains, this approach may be used to test the Bayesian brain hypothesis in order to understand the perception and sensory-motor coupling, on based of human brain deal with incoming sensory information in a probabilistic manner. Dynamic causal models of perceptual-motor coupling based on external modulation of sensory processing may provide an opportunity to achieve “effective” cross-talk between industrial engineering and basic neuroscientists (Kahan and Foltynie, 2013). By means of effective neurophysiological studies, we may be able to understand why drivers with similar sensory systems perform differently (i.e., very well or very badly) during automobile activity.

References

VanRullen, R., and Koch, C. (2003). Is perception discrete or continuous?. *Trends in Cognitive Sciences* 7, 207–213. doi:10.1016/s1364-6613(03)00095-0.

Friston, K. J., Daunizeau, J., Kilner, J., and Kiebel, S. J. (2010). Action and behavior: a free-energy formulation. *Biological Cybernetics* 102, 227–260. doi:10.1007/s00422-010-0364-z.

Asplund, C. L., Fougnie, D., Zughni, S., Martin, J. W., and Marois, R. (2014). The Attentional Blink Reveals the Probabilistic Nature of Discrete Conscious Perception. *Psychological Science* 25, 824–831. doi:10.1177/0956797613513810.

Thibault, L., Berg, R. van den, Cavanagh, P., and Sergent, C. (2016). Retrospective Attention Gates Discrete Conscious Access to Past Sensory Stimuli. *PLOS ONE* 11, e0148504. doi:10.1371/journal.pone.0148504.

Seth, A. K., Dienes, Z., Cleeremans, A., Overgaard, M., and Pessoa, L. (2008). Measuring consciousness: relating behavioural and neurophysiological approaches. *Trends in Cognitive Sciences* 12, 314–321. doi:10.1016/j.tics.2008.04.008.

VanRullen, R. (2016). Perceptual Cycles. *Trends in Cognitive Sciences* 20, 723–735. doi:10.1016/j.tics.2016.07.006.

Sergent, C., and Dehaene, S. (2004). Is Consciousness a Gradual Phenomenon?: Evidence for an All-or-None Bifurcation During the Attentional Blink. *Psychological Science* 15, 720–728. doi:10.1111/j.0956-7976.2004.00748.x.

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society B: Biological Sciences* 360, 815–836. doi:10.1098/rstb.2005.1622.

Buzsaki, G. (2006). *Rhythms of the Brain*. Oxford University Press.

Varela, F., Lachaux, J.-P., Rodriguez, E., and Martinerie, J. (2001). The brainweb: Phase synchronization and large-scale integration. *Nature Reviews Neuroscience* 2, 229–239. doi:10.1038/35067550.

Quyen, M. L. V. (2011). The brainweb of cross-scale interactions. *New Ideas in Psychology* 29, 57–63. doi:10.1016/j.newideapsych.2010.11.001.

Quyen, M. L. V., and Bragin, A. (2007). Analysis of dynamic brain oscillations: methodological advances. *Trends in Neurosciences* 30, 365–373. doi:10.1016/j.tins.2007.05.006.

Bagdasaryan, J., and Quyen, M. L. V. (2013). Experiencing your brain: neurofeedback as a new bridge between neuroscience and phenomenology. *Frontiers in Human Neuroscience* 7. doi:10.3389/fnhum.2013.00680.

Hasson, U., Yang, E., Vallines, I., Heeger, D. J., and Rubin, N. (2008). A Hierarchy of Temporal Receptive Windows in Human Cortex. *Journal of Neuroscience* 28, 2539–2550. doi:10.1523/jneurosci.5487-07.2008.

Spaak, E., Bonnefond, M., Maier, A., Leopold, D. A., and Jensen, O. (2012). Layer-Specific Entrainment of Gamma-Band Neural Activity by the Alpha Rhythm in Monkey Visual Cortex. *Current Biology* 22, 2313–2318. doi:10.1016/j.cub.2012.10.020.

Spaak, E., Lange, F. P. de, and Jensen, O. (2014). Local Entrainment of Alpha Oscillations by Visual Stimuli Causes Cyclic Modulation of Perception. *Journal of Neuroscience* 34, 3536–3544. doi:10.1523/jneurosci.4385-13.2014.

Arnal, L. H., and Kleinschmidt, A. K. (2017). Entrained delta oscillations reflect the subjective tracking of time. *Communicative & Integrative Biology* 10, e1349583. doi:10.1080/19420889.2017.1349583.

Ronconi, L., and Melcher, D. (2017). The role of oscillatory phase in determining the temporal organization of perception: evidence from sensory entrainment. *The Journal of Neuroscience*, 1704–17. doi:10.1523/jneurosci.1704-17.2017.

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

Nunes, L., and Recarte, M. A. (2002). Cognitive demands of hands-free-phone conversation while driving. *Transportation Research Part F: Traffic Psychology and Behaviour* 5, 133–144. doi:10.1016/s1369-8478(02)00012-8.

Wutz, A., Weisz, N., Braun, C., and Melcher, D. (2014). Temporal windows in visual processing: "prestimulus brain state" and "poststimulus phase reset" segregate visual transients on different temporal scales. *Journal of Neuroscience* 34, 1554–1565.

Thut, G., Schyns, P. G., and Gross, J. (2011). Entrainment of Perceptually Relevant Brain Oscillations by Non-Invasive Rhythmic Stimulation of the Human Brain. *Frontiers in Psychology* 2. doi:10.3389/fpsyg.2011.00170.

Mehler, B., Reimer, B., Coughlin, J. F., and Dusek, J. A. (2009). Impact of Incremental Increases in Cognitive Workload on Physiological Arousal and Performance in Young Adult Drivers. *Transportation Research Record: Journal of the Transportation Research Board* 2138, 6–12. doi:10.3141/2138-02.

Thiffault, P., and Bergeron, J. (2003). Monotony of road environment and driver fatigue: a simulator study. *Accident Analysis & Prevention* 35, 381–391. doi:10.1016/s0001-4575(02)00014-3.

Lal, S. K. L., and Craig, A. (2001). A critical review of the psychophysiology of driver fatigue. *Biological Psychology* 55, 173–194. doi:10.1016/s0301-0511(00)00085-5.

Klinestiver, L. R. (1980). Psychophysiological and other factors affecting human performance in accident prevention and investigation. EG and G Idaho.

Caird, J. K., Johnston, K. A., Willness, C. R., Asbridge, M., and Steel, P. (2014). A meta-analysis of the effects of texting on driving. *Accident Analysis & Prevention* 71, 311–318.

Drews, F. A., Pasupathi, M., and Strayer, D. L. (2008). Passenger and cell phone conversations in simulated driving.. *Journal of Experimental Psychology: Applied* 14, 392.

Henríquez, R. A., Chica, A. B., Billeke, P., and Bartolomeo, P. (2016). Fluctuating Minds: Spontaneous Psychophysical Variability during Mind-Wandering.. *PLoS One* 11, e0147174.

Thomson, D. R., Seli, P., Besner, D., and Smilek, D. (2014). On the link between mind wandering and task performance over time. *Consciousness and Cognition* 27, 14–26. doi:10.1016/j.concog.2014.04.001.

Yanko, M. R., and Spalek, T. M. (2014). Driving with the wandering mind: the effect that mind-wandering has on driving performance. *Human factors* 56, 260–269.

He, J., Becic, E., Lee, Y. C., and McCarley, J. S. (2011). Mind wandering behind the wheel: performance and oculomotor correlates.. *Hum Factors* 53, 13–21.

Horberry, T., Anderson, J., Regan, M. A., Triggs, T. J., and Brown, J. (2006). Driver distraction: The effects of concurrent in-vehicle tasks, road environment complexity and age on driving performance. *Accident Analysis & Prevention* 38, 185–191.

Ball, K., and Owsley, C. (1993). The useful field of view test: a new technique for evaluating age-related declines in visual function.. *Journal of the American Optometric Association* 64, 71–79.

Petridou, E., and Moustaki, M. (2000). Human factors in the causation of road traffic crashes. *European journal of epidemiology* 16, 819–826.

Basso, F., Basso, L. J., Bravo, F., and Pezoa, R. (2018). Real-time crash prediction in an urban expressway using disaggregated data. *Transportation Research Part C: Emerging Technologies* 86, 202–219.

Michon, J. A. (1985). “A critical view of driver behavior models: what do we know, what should we do?,” in *Human behavior and traffic safety* (Springer), 485–524.

Wilde, G. J. S. (1998). Risk homeostasis theory: an overview. *Injury prevention* 4, 89–91.

Menary, R. (2013). Cognitive integration enculturated cognition and the socially extended mind. *Cognitive Systems Research* 25-26, 26–34. doi:10.1016/j.cogsys.2013.05.002.

Gallagher, S., and Crisafi, A. (2008). Mental Institutions. *Topoi* 28, 45–51. doi:10.1007/s11245-008-9045-0.

Lee, J. D., Young, K. L., and Regan, M. A. (2008). Defining driver distraction. *Driver distraction: Theory, effects, and mitigation* 13, 31–40.

Walter, H., Vetter, S. C., Grothe, J. O., Wunderlich, A. P., Hahn, S., and Spitzer, M. (2001). The neural correlates of driving. *Neuroreport* 12, 1763–1767.

Deery, H. A. (1999). Hazard and Risk Perception among Young Novice Drivers. *Journal of Safety Research* 30, 225–236. doi:10.1016/s0022-4375(99)00018-3.

Ranney, T. A. (1994). Models of driving behavior: A review of their evolution. *Accident Analysis & Prevention* 26, 733–750. doi:10.1016/0001-4575(94)90051-5.

McGwin Jr, G., Owsley, C., and Ball, K. (1998). Identifying crash involvement among older drivers: agreement between self-report and state records. *Accident Analysis & Prevention* 30, 781–791.

McGwin Jr, G., and Brown, D. B. (1999). Characteristics of traffic crashes among young, middle-aged, and older drivers. *Accident Analysis & Prevention* 31, 181–198.

Lyman, S., Ferguson, S. A., Braver, E. R., and Williams, A. F. (2002). Older driver involvements in police reported crashes and fatal crashes: trends and projections. *Injury prevention* 8, 116–120.

Preusser, D. F., Williams, A. F., Ferguson, S. A., Ulmer, R. G., and Weinstein, H. B. (1998). Fatal crash risk for older drivers at intersections. *Accident Analysis & Prevention* 30, 151–159.

Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., and Bruni, J. R. (1991). Visual/cognitive correlates of vehicle accidents in older drivers.. *Psychology and aging* 6, 403.

Jensen, O., Bonnefond, M., and VanRullen, R. (2012). An oscillatory mechanism for prioritizing salient unattended stimuli. *Trends in Cognitive Sciences* 16, 200–206. doi:10.1016/j.tics.2012.03.002.

Geisler, W. S., and Kersten, D. (2002). Illusions perception and Bayes. *Nature Neuroscience* 5, 508–510. doi:10.1038/nn0602-508.

Friston, K., Samothrakis, S., and Montague, R. (2012). Active inference and agency: optimal control without cost functions. *Biological Cybernetics* 106, 523–541. doi:10.1007/s00422-012-0512-8.

Moutoussis, M., Trujillo-Barreto, N. J., El-Deredy, W., Dolan, R. J., and Friston, K. J. (2014). A formal model of interpersonal inference. *Frontiers in Human Neuroscience* 8. doi:10.3389/fnhum.2014.00160.

Moutoussis, M., Fearon, P., El-Deredy, W., Dolan, R. J., and Friston, K. J. (2014). Bayesian inferences about the self (and others): A review. *Consciousness and Cognition* 25, 67–76. doi:10.1016/j.concog.2014.01.009.

Buckley, C. L., Kim, C. S., McGregor, S., and Seth, A. K. (2017). The free energy principle for action and perception: A mathematical review. *Journal of Mathematical Psychology* 81, 55–79. doi:10.1016/j.jmp.2017.09.004.

Friston, K. J., and Frith, C. D. (2015). Active inference communication and hermeneutics. *Cortex* 68, 129–143. doi:10.1016/j.cortex.2015.03.025.

Buzsáki, G. (2004). Large-scale recording of neuronal ensembles. *Nature neuroscience* 7, 446.

Hutcheon, B., and Yarom, Y. (2000). Resonance oscillation and the intrinsic frequency preferences of neurons. *Trends in Neurosciences* 23, 216–222. doi:10.1016/s0166-2236(00)01547-2.

Whittington, M. A., Stanford, I. M., Colling, S. B., Jefferys, J. G. R., and Traub, R. D. (1997). Spatiotemporal patterns of frequency oscillations tetanically induced in the rat hippocampal slice. *The Journal of Physiology* 502, 591–607. doi:10.1111/j.1469-7793.1997.591bj.x.

Lőrincz, M. L., Kékesi, K. A., Juhász, G., Crunelli, V., and Hughes, S. W. (2009). Temporal Framing of Thalamic Relay-Mode Firing by Phasic Inhibition during the Alpha Rhythm. *Neuron* 63, 683–696. doi:10.1016/j.neuron.2009.08.012.

Jensen, O., and Mazaheri, A. (2010). Shaping Functional Architecture by Oscillatory Alpha Activity: Gating by Inhibition. *Frontiers in Human Neuroscience* 4. doi:10.3389/fnhum.2010.00186.

Salinas, E., and Sejnowski, T. J. (2001). Correlated neuronal activity and the flow of neural information. *Nature Reviews Neuroscience* 2, 539–550. doi:10.1038/35086012.

Fries, P. (2005). A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. *Trends in cognitive sciences* 9, 474–480.

Palva, S., and Palva, J. M. (2007). New vistas for alpha-frequency band oscillations.. *Trends Neurosci* 30, 150–8.

Stein, A. von, Chiang, C., and Konig, P. (2000). Top-down processing mediated by interareal synchronization. *Proceedings of the National Academy of Sciences* 97, 14748–14753. doi:10.1073/pnas.97.26.14748.

Akam, T., and Kullmann, D. M. (2014). Oscillatory multiplexing of population codes for selective communication in the mammalian brain. *Nature Reviews Neuroscience* 15, 111–122. doi:10.1038/nrn3668.

Jensen, O., and Colgin, L. L. (2007). Cross-frequency coupling between neuronal oscillations. *Trends in Cognitive Sciences* 11, 267–269. doi:10.1016/j.tics.2007.05.003.

Canolty, R. T., and Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends in Cognitive Sciences* 14, 506–515. doi:10.1016/j.tics.2010.09.001.

Thut, G., and Miniussi, C. (2009). New insights into rhythmic brain activity from TMS–EEG studies. *Trends in Cognitive Sciences* 13, 182–189. doi:10.1016/j.tics.2009.01.004.

Worden, M. S., Foxe, J. J., Wang, N., and Simpson, G. V. (2000). Anticipatory Biasing of Visuospatial Attention Indexed by Retinotopically Specific -Bank Electroencephalography Increases over Occipital Cortex. *The Journal of Neuroscience* 20, RC63–RC63. doi:10.1523/jneurosci.20-06-j0002.2000.

Sauseng, P., Klimesch, W., Stadler, W., Schabus, M., Doppelmayr, M., Hanslmayr, S., et al. (2005). A shift of visual spatial attention is selectively associated with human EEG alpha activity. *European Journal of Neuroscience* 22, 2917–2926. doi:10.1111/j.1460-9568.2005.04482.x.

Kelly, S. P., Lalor, E. C., Reilly, R. B., and Foxe, J. J. (2006). Increases in Alpha Oscillatory Power Reflect an Active Retinotopic Mechanism for Distracter Suppression During Sustained Visuospatial Attention. *Journal of Neurophysiology* 95, 3844–3851. doi:10.1152/jn.01234.2005.

Pikovsky, A., Rosenblum, M., Kurths, J., and Kurths, J. (2003). *Synchronization: a universal concept in nonlinear sciences.* Cambridge university press.

Glass, L. (2001). Synchronization and rhythmic processes in physiology. *Nature* 410, 277–284. doi:10.1038/35065745.

Lakatos, P., Karmos, G., Mehta, A. D., Ulbert, I., and Schroeder, C. E. (2008). Entrainment of Neuronal Oscillations as a Mechanism of Attentional Selection. *Science* 320, 110–113. doi:10.1126/science.1154735.

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

VanRullen, R., Reddy, L., and Koch, C. (2005). Attention-driven discrete sampling of motion perception. *Proceedings of the National Academy of Sciences* 102, 5291–5296. doi:10.1073/pnas.0409172102.

Wutz, A., Melcher, D., and Samaha, J. (2018). Frequency modulation of neural oscillations according to visual task demands. *Proceedings of the National Academy of Sciences* 115, 1346–1351. doi:10.1073/pnas.1713318115.

VanRullen, R., Guyonneau, R., and Thorpe, S. J. (2005). Spike times make sense. *Trends in Neurosciences* 28, 1–4. doi:10.1016/j.tins.2004.10.010.

Khaliliardali, Z., Chavarriaga, R., Gheorghe, L. A., and Millan, J. R. del (2012). Detection of anticipatory brain potentials during car driving. in *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (IEEE). doi:10.1109/embc.2012.6346802.

Kahan, J., and Foltynie, T. (2013). Understanding DCM: Ten simple rules for the clinician. *NeuroImage* 83, 542–549. doi:10.1016/j.neuroimage.2013.07.008.