Emotional Detours: Oscillatory Signatures of Emotion and Cognitive Load during Simulated Driving

Katharina Lingelbach[1,2], Jochem W. Rieger[1]

[1] Applied Neurocognitive Psychology, Department of Psychology, Carl von Ossietzky University, Oldenburg, Germany

[2] Applied Neurocognitive Systems, Fraunhofer Institute for Industrial Engineering IAO, Stuttgart, Germany

Synopsis

Driving is a complex task that requires many cognitive processes. The allocation of cognitive resources may differ depending on the level of induced cognitive load and the emotional context. Research on such interacting processes and underlying neurophysiological signatures remains scarce. In this study, we investigated the interaction of emotional auditory processing and task load during simulated driving using magnetoencephalography. Oscillatory signatures and indices for cognitive load, attention, and emotion processing were analysed. We observed increased fronto-temporal theta oscillations during emotional compared to neutral speech, suggesting the recruitment of executive functions. Increased parieto-temporal alpha and beta power potentially indicate functional inhibition of emotion-based processes. Our findings on emotional and cognitive states in real-world scenarios provide valuable insights for interdisciplinary research on road safety and automotive engineering.

Background

During driving, several cognitive processes are required, including visuospatial attention and working memory, to process signals and respond adequately (Fort et al., 2010). In naturalistic scenarios, cognitive resources are allocated not only to driving but also to environmental stimuli, such as conversations with other passengers. Particularly, stimuli that are emotionally significant capture attentional resources (Adolphs, 2003; Tamietto & Gelder, 2010; Vuilleumier, 2005). Oscillatory brain activation allows for studying attention and cognitive load (Chikhi et al., 2022; Senkowski et al. 2005) as well as emotional processing (e.g., Briesemeister et al., 2013). In neuroergonomic electroencephalography (EEG) research, specific power ratios are proposed to indicate workload (WI; frontal theta (4 – 7 Hz) to parietal alpha (8 – 12 Hz); Gevins et al., 1995; Raufi & Longo, 2022) and engagement (EI; centro-parietal beta (15 – 25 Hz) to alpha; Kislov et al., 2022; Pope et al., 1995). A frontal alpha asymmetry (FFA) is believed to be valence-sensitive, indicating negative emotions through increased right-hemispheric power and positive emotions through left-hemispheric power (Ahern & Schwartz, 1985; Briesemeister et al., 2013; Smith et al., 2017).

Previous neurophysiological research on driving has predominantly concentrated on workload and attention-related processes, without addressing interacting emotional processes (Li et al., 2023; Liu et al., 2023; Sakihara et al., 2014; Simon et al., 2011; Simpson & Rafferty, 2022; Wascher et al., 2018). Studies investigating the interaction of emotional and cognitive processes often lack ecological validity in terms of stimuli and experimental tasks (for reviews see Cromheeke et al., 2014; Dolcos et al., 2011; Schweizer et al., 2019).

We conducted a whole-head magnetoencephalography (MEG) study with simulated driving (Figure 1A) and concurrently presented naturalistic emotional audio speech with sequences of low (LV), neutral (NV), and high (HV) valence from the validated GAUDIE database (Lingelbach et al, 2023).

We hypothesised that for low cognitive load (LW) drives, LV (negative emotion) and HV (positive emotion) but not NV (neutral emotion) speech captures attention; however, without major interference with cognitive processes. During high cognitive load (HW) drives, HV and NV speech effects can be downregulated by executive control. Assuming that LV speech is particularly potent in interfering with cognition, it may overcome regulation and compete for task-related resources, causing interference between cognitive and emotional processing.

Methods

Forty-eight participants were included in the study. During LW (Figure 1B, upper row), participants drove on a highway with average traffic and predictable agents. During HW (Figure 1B, lower row), they navigated through construction areas with less predictable agents. At the end of each block, participants rated their experienced valence, effort, and distraction.

Brain signals were corrected for movements and external interference, bandpass filtered (4^{th}-order IIR with 0.1 - 42 Hz), downsampled, and cleaned from ocular and cardiac artefacts. Afterwards, the continuous signals were epoched into non-overlapping windows of 5s and planar gradiometers were combined. Power spectra were computed using multitapers with a bandwidth of 2.

To investigate topographic activation in the frequency bands of interest (theta, alpha, and beta), we applied spatial clustering using repeated-measures ANOVAs and post-hoc *t*-tests to reveal significant clusters. Additionally, effects in power indices (FFA, WI, and EI) and subjective ratings were analysed using linear mixed models and Monte-Carlo-Simulation based bootstrapping.

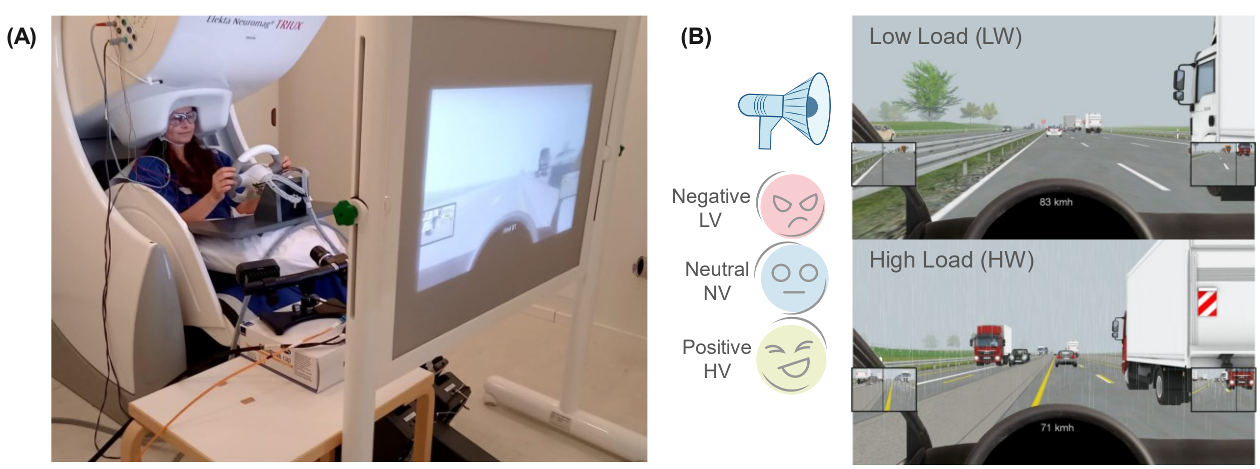

Figure 1 (A) Experimental set-up of the driving simulator and realistic vehicle mock-up with a steering wheel, throttle, and brake pedal. Participants were seated in the MEG inside the magnetically shielded chamber. (B) Overview of the within-subject design (factors: *workload* x *emotion*) with six conditions presented block-wise. During the driving block either negative (LV),

neutral (NV) or positive (HV) audio sequences were presented concurrently during either a low (LW) or high (HW) load driving sequence.

Results

The topographic cluster analysis revealed valence effects in the theta, alpha, and beta band power, as well as a cognitive load effect in the beta band power (Figure 2AB). Two lateralised frontotemporal clusters showed increased theta power for HV and LV compared to NV (Figure 2C, D, left). LV elicited particularly pronounced right-hemispheric temporal theta power. Increased alpha power was observed for emotional speech, mainly bilaterally in temporal regions, but also in frontal and parietal regions (Figure 2CD, middle). Beta power was enhanced during emotional speech across temporal and parietal regions, with right-lateralized effects (Figure 2CD, right). Increased load was associated with decreased occipito-parietal beta power (Figure 2E).

We observed a workload effect with higher WI during HW (Figure 2F). There were trends for emotion effects for WI and EI with increases and decreases for NV, respectively. An emotion effect for the FFA revealed increased right frontal alpha for HV and LV.

Subjective ratings uncovered workload and emotion effects on effort and valence. HW compared to LW as well as LV and NV compared to HV increased perceived effort and reduced valence during the block. An interaction trend suggested that only NV and HV valence ratings were affected by task load. A significant effect of emotion indicated increased distraction by LV (Figure 2G).

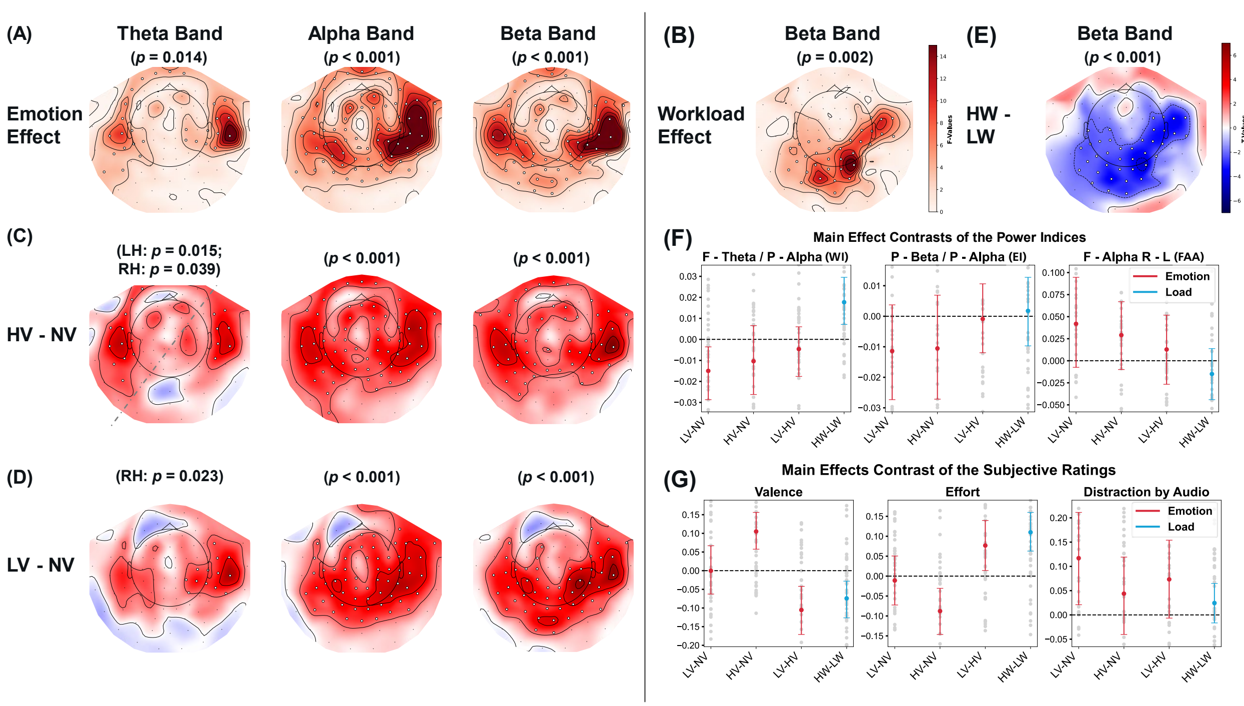

Figure 2 Significant topographic clusters with *F*-values from the spatial permutation-based rmANOVAs for the (A) main emotion effects in the power of the theta, alpha, and beta frequency bands, and (B) main workload effect in the beta frequency band power. Significant topographic clusters with *t*-values of the post-hoc contrasts (C) HV-NV, (D) LV-NV, and (E) HW-LW.

Significant channels are depicted as white circles. (F) Grand averages and Bonferroni-corrected confidence intervals of the main effect contrasts for each power index. WI: Workload Index, EI: Engagement Index, FAA: Frontal Alpha Asymmetry, F: Frontal, P: Parietal, R: Right, L: Left. Defined frequency band cut-offs: theta with 4 – 7 Hz, alpha with 8 – 12 Hz, beta with 15 – 25 Hz. G) Grand averages and Bonferroni-corrected confidence intervals of the main effect contrasts for the subjective ratings valence, effort, and distraction by audio sequence. LV: Low Valence, HV: High Valence, NV: Neutral Valence, HW: High Workload, LW: Low Workload.

Discussion

In our investigation of the interaction between emotional speech and driving load, fronto-temporal theta oscillations increased during negative and positive compared to neutral speech sequences. This suggests the recruitment of executive control mechanisms (Lowe et al., 2018; Rajan et al., 2019), the allocation of attentional resources between the visuo-spatial driving task and emotional auditory stimuli (Lin et al., 2011; Liu et al., 2023; Sakihara et al., 2014) and reallocation of directed attention (Fellrath et al., 2016; Kam et al., 2019), probably towards the road. Additionally, we observed increased parieto-temporal inhibition (Klimesch et al., 2007), potentially indicating suppression of (right) temporo-parietal activation, triggered by emotional speech (Lettieri et al., 2019). The workload effect is characterised by a decrease in occipital beta oscillations, which can be attributed to reduced functional inhibition and enhanced visual processing during high-load drives (e.g., Liu et al., 2023). We did not observe an interaction effect between load and emotional speech. When examining the power indices, the WI was able to differentiate between workloads. However, it showed inconsistent emotion effects when compared to the subjective ratings. The FFA was able to identify emotions but was not sensitive to valence. Therefore, these indices were found to be less suitable for researching interacting cognitive processes.

In the future, we intend to extend and combine the neurophysiological data with eye tracking in order to analyse specific fixation- and blink-locked events (Alyan et al., 2023). In addition, future research could replicate these findings using mobile brain sensors (e.g., fNIRS and EEG) to facilitate sensor integration into a car interior and real-world application.

Our research of cognitive and emotional states in naturalistic driving scenarios contributes to the understanding of safety-critical states such as inattentiveness or overload. This enables us to derive implications for traffic safety and automotive engineering, for instance, in the development of assistance systems.

Funding

The research was supported by the Fraunhofer Gesellschaft with the scholarship »Fraunhofer TALENTA« (K. Lingelbach), the Ministry of Economic Affairs, Labour, and Tourism Baden-Wuerttemberg in the project »KI-Fortschrittszentrum Lernende Systeme und Kognitive Robotik« (Fraunhofer IAO), the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation; RI 1511/3-1; J. Rieger) and the Neuroimaging Unit of the Carl von Ossietzky Universität Oldenburg funded by grants from the DFG (3T MRI INST 184/152-1 FUGG and MEG INST 184/148-1 FUGG).

References

(Adolphs, 2003) Adolphs, R. (2003). Cognitive neuroscience of human social behaviour. Nature Reviews. Neuroscience, 4(3), 165–178. https://doi.org/10.1038/nrn1056

(Ahern & Schwartz, 1985) Ahern, G. L., & Schwartz, G. E. (1985). Differential lateralisation for positive and negative emotion in the human brain: EEG spectral analysis. Neuropsychologia 23, 745–755. https://doi.org/10.1016/0028-3932(85)90081-8

(Alyan et al., 2023) Alyan, E., Arnau, S., Reiser, J. E., Getzmann, S., Karthaus, M., & Wascher, E. (2023). Blink-related EEG activity measures cognitive load during proactive and reactive driving. Sci Rep, 13, 19379. https://doi.org/10.1038/s41598-023-46738-0

(Briesemeister et al., 2013) Briesemeister, B. B., Tamm, S., Heine, A., & Jacobs, A. M. (2013). Approach the good, withdraw from the bad—A review on frontal alpha asymmetry measures in applied psychological research. PSYCH 04, 261–267. https://doi.org/10.4236/psych.2013.43A039

(Chikhi et al., 2022) Chikhi, S., Matton, N., & Blanchet, S. (2022). EEG power spectral measures of cognitive workload: A meta-analysis. Psychophysiology, 59(6), e14009. https://doi.org/10.1111/psyp.14009

(Cromheeke et al., 2014) Cromheeke, S., & Mueller, S. C. (2014). Probing emotional influences on cognitive control: An ALE meta-analysis of cognition emotion interactions. Brain Structure & Function, 219(3), 995–1008. https://doi.org/10.1007/s00429-013-0549-z

(Dolcos et al., 2011) Dolcos, F., Iordan, A. D., & Dolcos, S. (2011). Neural correlates of emotion-cognition interactions: A review of evidence from brain imaging investigations. Journal of Cognitive Psychology (Hove, England), 23(6), 669–694. https://doi.org/10.1080/20445911.2011.594433

(Fellrath et al., 2016) Fellrath, J., Mottaz, A., Schnider, A., Guggisberg, A. G., & Ptak, R. (2016). Theta-band functional connectivity in the dorsal fronto-parietal network predicts goal-directed attention. Neuropsychologia, 92, 20–30. https://doi.org/10.1016/j.neuropsychologia.2016.07.012

(Fort et al., 2010) Fort, A., Martin, R., Jacquet-Andrieu, A., Combe-Pangaud, C., Foliot, G., Daligault, S., & Delpuech, C. (2010). Attention and processing of relevant visual information while simulated driving: a MEG study. Brain research, 1363. https://doi.org/10.1007/978-3-642-12197-5_75

(Gevins et al., 1995) Gevins, A., Leong, H., Du, R., Smith, M. E., Le, J., DuRousseau, D., Zhang, J., & Libove, J. (1995). Towards measurement of brain function in operational environments. Biological Psychology, 40(1-2), 169–186. https://doi.org/10.1016/0301-0511(95)05105-8

(Kam et al., 2019) Kam, J. W. Y., Lin, J. J., Solbakk, A. K., Endestad, T., Larsson, P. G., & Knight, R. T. (2019). Default network and frontoparietal control network theta connectivity supports internal attention. Nat Hum Behav 3, 1263–1270.https://doi.org/10.1038/s41562-019-0717-0

(Kislov et al., 2022) Kislov, A., Gorin, A., Konstantinovsky, N., Klyuchnikov, V., Bazanov, B., & Klucharev, V. (2022). Central EEG Beta/Alpha Ratio Predicts the Population-Wide Efficiency of Advertisements. Brain sciences, 13(1), 57. https://doi.org/10.3390/brainsci13010057

(Klimesch et al., 2007) Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007): EEG alpha oscillations: the inhibition-timing hypothesis. In: Brain research reviews 53 (1), S. 63–88. DOI: 10.1016/j.brainresrev.2006.06.003.

(Lettieri et al., 2019) Lettieri, G., Handjaras, G., Ricciardi, E., Leo, A., Papale, P., Betta, M., Pietrini, P., & Cecchetti, L. (2019). Emotionotopy in the human right temporo-parietal cortex. Nature communications, 10(1), 5568. https://doi.org/10.1038/s41467-019-13599-z

(Li et al. 2023) Li, G., Wu, X., Eichberger, A., Green, P., Olaverri-Monreal, C., Yan, W., Qin. Y., & Li, Y. (2023). Drivers' EEG Responses to Different Distraction Tasks. Automot. Innov. 6, 20–31. https://doi.org/10.1007/s42154-022-00206-z

(Lin et al., 2011) Lin, C. T., Chen, S. A., Chiu, T. T., Lin, H. Z., & Ko, L. W. (2011). Spatial and temporal EEG dynamics of dual-task driving performance. Journal of neuroengineering and rehabilitation, 8, 11. https://doi.org/10.1186/1743-0003-8-11

(Lingelbach et al. 2023) Lingelbach, K., Vukelić, M., & Rieger, J. W. (2023). GAUDIE: Development, validation, and exploration of a naturalistic German AUDItory Emotional database. Behav Res. https://doi.org/10.3758/s13428-023-02135-z

(Liu et al., 2023) Liu, R., Qi, S., Hao, S., Lian, G. & Luo, Y. (2023) Using electroencephalography to analyse drivers' different cognitive workload characteristics based on on-road experiment. Front. Psychol. 14:1107176. doi: 10.3389/fpsyg.2023.1107176

(Lowe et al., 2018) Lowe, C. J., Manocchio, F., Safati, A. B., & Hall, P. A. (2018). The effects of theta burst stimulation (TBS) targeting the prefrontal cortex on executive functioning: a systematic review and meta-analysis. Neuropsychologia, 111, 344-359.

(Rajan et al., 2019) Rajan, A., Siegel, S. N., Liu, Y., Bengson, J., Mangun, G. R., & Ding, M. (2019). Theta oscillations index frontal decision-making and mediate reciprocal frontal–parietal interactions in willed attention. Cerebral cortex, 29(7), 2832-2843.

(Sakihara et al., 2014) Sakihara, K., Hirata, M., Ebe, K., Kimura, K., Yi Ryu, S., Kono, Y., Muto, N., Yoshioka, M., Yoshimine, T., & Yorifuji, S. (2014). Cerebral oscillatory activity during simulated driving using MEG. Front. Hum. Neurosci. 8:975. doi: 10.3389/fnhum.2014.00975

(Schweizer et al., 2019) Schweizer, S., Satpute, A. B., Atzil, S., Field, A. P., Hitchcock, C., Black, M., Barrett, L. F., & Dalgleish, T. (2019). The impact of affective information on working memory: A pair of meta-analytic reviews of behavioral and neuroimaging evidence. Psychological Bulletin, 145(6), 566–609. https://doi.org/10.1037/bul0000193

(Senkowski et al., 2005) Senkowski, D., Talsma, D., Herrmann, C. S. & Woldorff, M. G. (2005). Multisensory processing and oscillatory gamma responses: effects of spatial selective attention. Exp Brain Res 166, 411–426. https://doi.org/10.1007/s00221-005-2381-z

(Simon et al., 2011) Simon, M., Schmidt, E. A., Kincses, W. E., Fritzsche, M., Bruns, A., Aufmuth, C., Bogdan, M., Rosenstiel, W., & Schrauf, M. (2011). EEG alpha spindle measures as indicators of driver fatigue under real traffic conditions. Clinical Neurophysiology, 122 (6), 1168-1178. https://doi.org/10.1016/j.clinph.2010.10.044

(Simpson & Rafferty, 2022) Simpson, T. G., & Rafferty, K. (2022). EEG Correlates of Driving Performance. IEEE Transactions on Human-Machine Systems, 52 (2), 232-247. doi: 10.1109/THMS.2021.3137032

(Smith et al., 2017) Smith, E. E., Reznik, S. J., Stewart, J. L., & Allen, J. J. B. (2017). Assessing and conceptualizing frontal EEG asymmetry: An updated primer on recording, processing, analyzing, and interpreting frontal alpha asymmetry. Int J Psychophysiol 111, 98–114. https://doi.org/10.1016/j.ijpsycho.2016.11.005

(Tamietto & Gelder, 2010) Tamietto, M., & Gelder, B. de (2010). Neural bases of the non-conscious perception of emotional signals. Nature Reviews. Neuroscience, 11(10), 697–709. https://doi.org/10.1038/nrn2889

(Pope et al., 1995) Pope, A. T., Bogart, E. H., & Bartolome, D. S. (1995). Biocybernetic system evaluates indices of operator engagement in automated task. Biological psychology, 40(1-2), 187-195. https://doi.org/10.1016/0301-0511(95)05116-3

(Raufi & Longo, 2022) Raufi, B., & Longo, L. (2022). An Evaluation of the EEG Alpha-to-Theta and Theta-to-Alpha Band Ratios as Indexes of Mental Workload. Frontiers in Neuroinformatics, 16, 861967. https://doi.org/10.3389/fninf.2022.861967

(Vuilleumier, 2005) Vuilleumier, P. (2005). How brains beware: Neural mechanisms of emotional attention. Trends in Cognitive Sciences, 9(12), 585–594. https://doi.org/10.1016/j.tics.2005.10.011

(Wascher et al., 2018) Wascher, E., Arnau, S., Gutberlet, I., Karthaus, M., & Getzmann S. (2018). Evaluating Pro- and Re-Active Driving Behavior by Means of the EEG. Front. Hum. Neurosci. 12:205. doi: 10.3389/fnhum.2018.00205