

Top-Down versus Bottom-up Processing in the Human Brain: Distinct Directional Influences Revealed by Integrating SOBI and Granger Causality

Akaysha C. Tang¹, Matthew T. Sutherland¹, Peng Sun², Yan Zhang³, Masato Nakazawa¹, Amy Korzekwa¹, Zhen Yang¹, Mingzhou Ding³

¹University of New Mexico, Department of Psychology, Albuquerque, NM, USA

²University of New Mexico, Department of Electrical Engineering, Albuquerque, NM, USA

³University of Florida, J. Crayton Pruitt Family Department of Biomedical Engineering, Gainesville, FL, USA

akaysha@unm.edu, msuther@unm.edu, pengsun@unm.edu, zhyang@unm.edu,
maliszt@unm.edu, akorzekw@unm.edu, mding@bme.flu.edu

Abstract. Top-down and bottom-up processing are two distinct yet highly interactive modes of neuronal activity underlying normal and abnormal human cognition. Here we characterize the dynamic processes that contribute to these two modes of cognitive operation. We used a blind source separation algorithm called second-order blind identification (SOBI [1]) to extract from high-density scalp EEG (128 channels) two components that index neuronal activity in two distinct local networks: one in the occipital lobe and one in the frontal lobe. We then applied Granger causality analysis to the SOBI-recovered neuronal signals from these two local networks to characterize feed-forward and feedback influences between them. With three repeated observations made at least one week apart, we show that feed-forward influence is dominated by alpha while feedback influence is dominated by theta band activity and that this direction-selective dominance pattern is jointly modulated by situational familiarity and demand for visual processing.

Keywords: electroencephalogram, second-order blind identification (SOBI), coherence, Granger causality, top-down, bottom-up, feed-forward, feedback.

1 Introduction

Second-order blind identification (SOBI) [1] is an emerging signal processing technique that can be used to facilitate source analysis from high-density EEG. Similar to other ICA algorithms that have been applied to EEG data [2], [3], SOBI can be used to isolate and remove ocular artifact [4]. In our laboratory, we have conducted extensive investigations to demonstrate the utility of SOBI in aiding source analysis from high-density EEG. Specifically, we have shown that: (1) SOBI can correctly recover known noise sources (noisy sensors and artificially injected noise at known electrodes) and known neuronal sources (SI activation by median nerve

stimulation) [5]; (2) SOBI can increase signal to noise ratios leading to improved performance in single-trial ERP classification [6]; (3) SOBI can recover neuronal sources whose activations are correlated [7]; (4) SOBI can recover neuronal sources using EEG collected when the brain is in its default mode (i.e., the “resting” state) [8]; (5) SOBI can recover neuronal sources during free viewing of continuous streams of visual information [9]; and (6) SOBI can recover weak neuronal signals that temporally overlap with much stronger signals (e.g. signals associated with ipsilateral activation of primary somatosensory cortex) [10].

In this paper, we set out to achieve three goals. First, we seek to provide further validation for SOBI recovered neuronal sources by investigating whether the same neuronal sources can be recovered from repeated EEG measures that are obtained days and weeks apart. Second, we combine SOBI with Granger causality analysis to show distinct patterns of theta(θ)/alpha(α) contributions in the feed-forward and feedback influences between the frontal and occipital cortices. Third, we investigate how such asymmetrical influence between the frontal and occipital cortices is modulated by sensory processing and by situational familiarity.

2 Methods

Eight right-handed subjects volunteered to participate in the present study. All subjects were free of any history of neurological or psychological disorders. The experimental procedures were conducted in accordance with the Human Research Review Committee at the University of New Mexico. Each subject was tested in three sessions at Week 0, Week 1, and Week 4 or later. Up to 7 min of continuous 128-channel EEG data were collected at 1000 Hz during: (1) eyes-closed “resting”; (2) eyes-open “resting”; (3) video-viewing (a silently played nature video); (4) listening to only the audio track of the video; and (5) forming mental images of scenes from the video. This paper limits the discussion to conditions 1-3.

SOBI was applied to the continuous EEG data $\mathbf{x}(t)$, across all conditions to extract the continuous time course of activation from two types of neuronal components--- an anterior (A) and a posterior (P) component. For details on SOBI application, see [5]. Briefly, SOBI recovers the underlying sources, $\mathbf{s}(t)$, by minimizing the sum squared cross-correlations between $\mathbf{s}_i(t)$ and $\mathbf{s}_j(t + \tau)$, across all pairs of sources and across multiple time delays, τ . A subset of SOBI-recovered components can be verified as neuronal sources via source localization using a forward model (e.g. BESA 5.0) [3]. Here we focused our analysis on two such neuronal components that correspond to focal regions within the frontal and occipital lobes.

Feed-forward (FF) and feedback (FB) influences were quantified by Granger causality between the two components, reflecting long-distance *directional* influences between the frontal and occipital cortices. Granger causality analysis was carried out on the continuous time courses, $\mathbf{s}_i(t)$, from the selected A and P components according to methods detailed in [11], [12]. As Granger causality can be decomposed into its frequency content, we computed Granger causality spectrum and measured power within the θ (4-7 Hz) and α (8-14 Hz) bands using a moving window of 30-sec with 5-

sec increments. Power in the θ and α bands from the A and P components were also computed as indicators of synchronization within the local networks.

3 Results

Reliable Extraction and Identification of Neuronal Components from Repeated Measures made Weeks Apart. In all 8 subjects, across all 3 sessions, we were able to recover SOBI components that corresponded to two distinct neuronal sources, one localized to a rather focal region within the frontal cortex, in or near anterior cingulate cortex (ACC) and the other to focal regions within the occipital lobe (occipital gyrus). Repeated-measure ANOVA revealed no statistically significant differences in the location of the corresponding ECD models across the 3 recording sessions. As no session-to-session difference was found, the averaged locations across the 3 sessions are shown in Fig. 1. ECDs for each of the 8 subjects are superimposed in the figure revealing a tight clustering of ECDs across subjects. This result demonstrates that SOBI can reliably recover components that correspond to anatomically well defined brain regions even when the recording sessions were made weeks apart.

It is important to emphasize that the recovery of these two neuronal sources was achieved without imposing constraints of fixation or use of event-related stimulation paradigms. Instead, subjects were allowed to freely move or blink their eyes as needed during the recording conditions. No segment of the EEG data was excluded prior to SOBI application. These unique features of SOBI processing have non-trivial

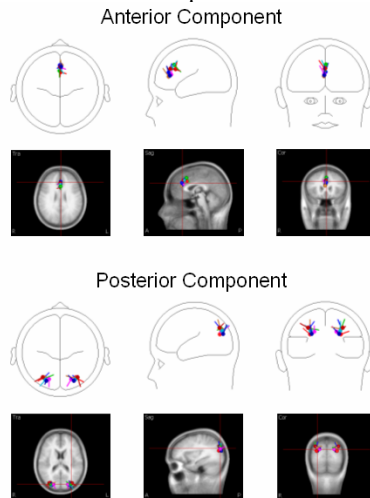


Fig. 1. Equivalent current dipole (ECD) locations for the SOBI recovered A and P components.

implications for the study of mental disorders and the study of early development or aging where subjects are often unable to conform to typical experimental constraints.

Theoretically, this result implies that SOBI's ability to recover anatomically well-defined neuronal sources does not depend upon the use of an event-related stimulation paradigm. Thus, fast electrical brain activity in the default mode [13] can be investigated in terms of neuronal signals originating from specific, focal cortical areas. In comparison to default mode activity revealed by fMRI, the default mode activity revealed with SOBI and EEG will offer millisecond temporal resolution, allowing for the characterization of default mode brain dynamics within a new temporal domain.

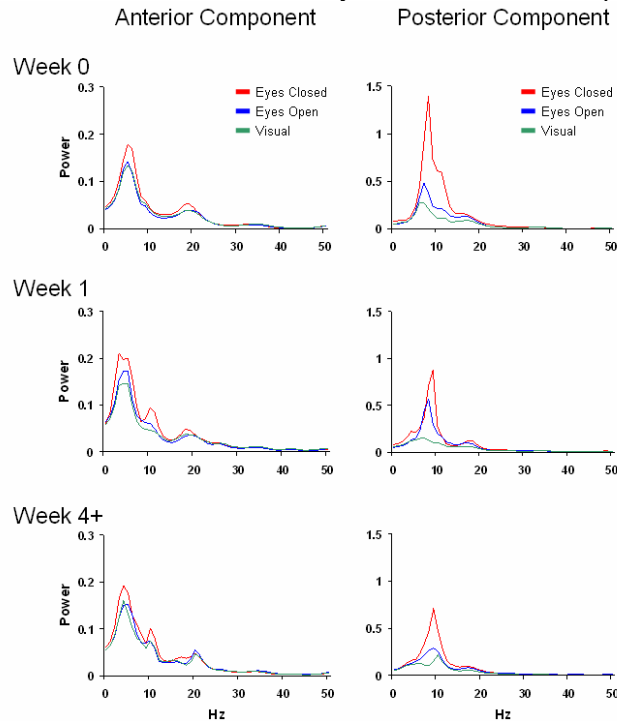


Fig. 2. Median power spectra of two SOBI-neuronal components as a function of repeated exposures to the same experimental situation. Session 1: week 0; Session 2: week 1; Session 3: week 4+.

Local Network Synchrony Shows Distinct Patterns of Change across 3 Repeated Exposures to the same Experimental Situation. For each of the 3 recording sessions, power spectra from the component time courses were computed for ~5-min segments during which the subjects had their eyes-closed (red), eyes-open (blue), or viewed a nature video (green), respectively (Fig. 2).

The anterior component had peak power within the θ band while the posterior component had peak power within the α band, indicated by a significant main effect of Region in the θ -to- α ratio ($F[1,7] = 52.12, p < 0.001, \text{partial } \eta^2 = 0.88$). This is consistent with the well established fact that the posterior and anterior parts of the brain are major sources of α and θ generators, respectively.

Power spectra in these two components were differentially modulated by sessions and experimental conditions [interaction effect: Region x Session (contrast coefficients: 1, -1, 0) x Condition (1, 0, -1), $F(1,7) = 3.52$, $p = 0.05$, 1-tailed, partial $\eta^2=0.33$]. For the P component, the power spectra revealed a systematic effect of session and experimental condition. Across the 3 repeated exposures to the same experimental conditions, peak α power decreased as the testing situation became increasingly familiar.

Across the 3 experimental conditions, the highest peak α power was associated with the eyes closed condition and the peak α power was successively reduced when the demand for visual processing increased from the eyes-closed to the eyes-open and video-viewing conditions. This latter observation is consistent with the known observation that visual processing suppresses α band activity. In contrast, for the anterior component, the power spectra showed a relative insensitivity to repeated exposures to the same experimental conditions and little modulation by the eyes-closed, eyes-open, and video-viewing conditions.

Differential Modulation of θ/α Contribution to Feed-Forward and Feedback Influences by Situational Familiarity and Visual Processing. FF (posterior-to-anterior) and FB (anterior-to-posterior) influences were measured by Granger causality in the θ and α band activity separately. FF and FB Granger causality measures were plotted as a function of time (Fig. 3). For the FF influence, when the eyes were closed, α band

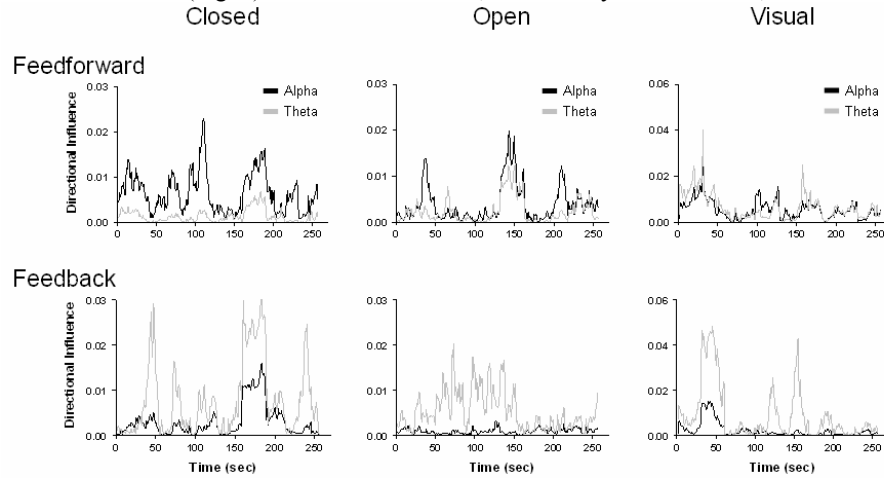


Fig. 3. Theta dominance over alpha in the anterior-to-posterior feedback (lower) influence and its reversal in the posterior-to-anterior feed-forward influence (upper) from a single-subject.

activity clearly dominated as indicated by the α waveforms (black) having greater area underneath the curve than the θ waveforms (grey). This α dominance was clearly reduced when the eyes were open and was further reduced to nearly non-existent when the subjects viewed a video. For the FB influence, the pattern of α dominance over θ was reversed showing uniform θ dominance over α across all 3 experimental conditions.

Using the area underneath the curve as a dependent measure, we summarize results from all 8 subjects across all 3 recording sessions in Fig. 4. To determine whether θ and α band activity contribute differentially to the FF and FB influences and how such differential contributions are modulated by situational familiarity and sensory processing, we performed an ANOVA on the θ/α ratio.

The θ/α ratio differed significantly between the FF and FB influences with a greater ratio for FB influence than for the FF influence (main effect of Direction, $F[1,7] = 34.64, p < 0.001, \text{partial } \eta^2 = 0.83$), i.e. a θ dominance in FB influence. This can be seen by the higher measures for the θ band activity than the α band activity for the FB influences in most of the 9 conditions and clear reversal or reduction of this θ dominance in the FF influence (Fig. 4).

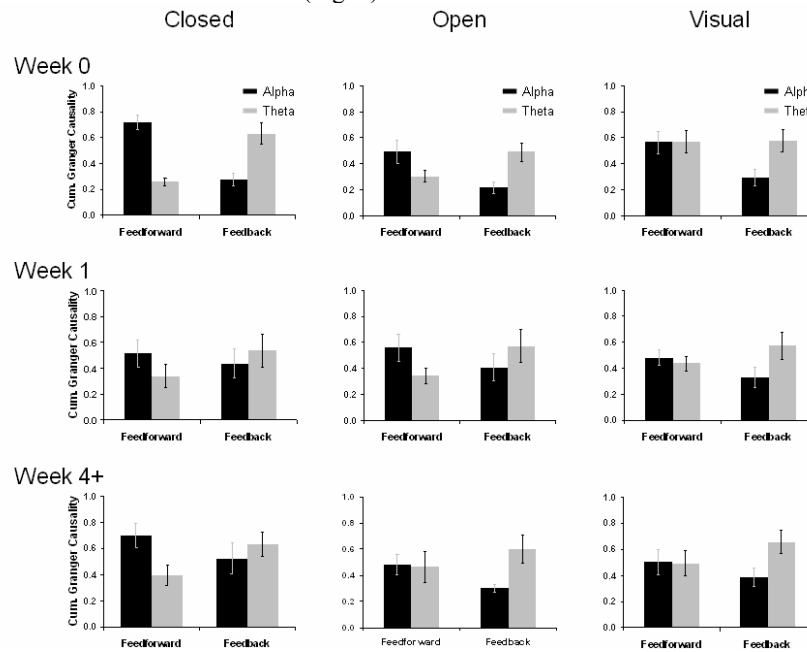


Fig. 4. Cumulative Granger Causality (area underneath the curve in Fig. 3) in the θ and α band as a function of situational familiarity (repeated sessions) and a function of visual processing (eyes-closed, eyes-open, video-viewing).

This reversal of θ dominance from FF and FB influences was significantly modulated by the familiarity of the situation [Direction x Session (contrast coefficients: 1, -1, 0), $F(1,7) = 11.97, p=0.005, 1\text{-tailed}, \text{partial } \eta^2=0.63$]. The reversal is more prominent when the situation was novel (Week 0) than when it became more familiar (Week 1 and 4+). This is best seen in the case of eyes-closed condition. The magnitude of reversal is clearly reduced from Week 0 in comparison to Week 4+.

For the eyes-open condition, the θ dominance was reversed in Week 0 and 1 and reduced in Week 4+. For the video-viewing condition, the reversal of θ dominance does not appear to be influenced by the increasing situational familiarity. These

patterns indicate that the FF/FB contrast is dependent upon the amount of visual information processing involved. When the subjects were engaged in visual perception during video-viewing, θ dominance in the FB influence and θ - α balance in the feed-forward influence are maintained across recording sessions. This visual processing-dependent effect is supported by a significant 3-way interaction [Direction x Session (1, -1, 0) x Condition (1, 0, -1), $F(1,7) = 7.13$, $p = 0.02$, 1-tailed partial $\eta^2=0.63$].

Within Week0 when the recording situation was novel (which is comparable to most studies that do not deal with the issue of task familiarity), θ dominance in the FB influence was maintained despite varying demand for visual processing. In contrast, the α dominance in the FF influence in the case of eyes-closed condition was reduced by increasing demand for sensory processing. In fact, visual processing was accompanied not only by a reduction in α but an increase in θ band activity in the FF influence. We speculate that this increase in θ band activity serves to “match” the θ -dominance in the FB influence to mediate the dynamic two-way communication between the posterior and anterior parts of the brain.

4 Discussion

We analyzed EEG data collected from 8 subjects in three sessions that were weeks apart, each including a period of resting with eyes-closed, resting with eyes-open, and visual perception while free viewing a nature video. We extracted neuronal signals from focal brain regions within the frontal and occipital lobes and showed that such extraction can be achieved under free viewing conditions and from recordings made weeks apart. As many intervening events must have taken place during the inter-session intervals, the reliable extraction of the neuronal sources raises the possibility that such a wide range of variations may be overcome by the use of SOBI in longitudinal experimental designs necessary for developmental and aging studies.

Applying Granger causality analysis to the time courses of the frontal and occipital SOBI components, we presented evidence indicating distinct patterns of θ/α band activity in the FF and FB influences between the two components, with a θ dominance characterizing the FB influence and an α dominance in the FF influence. By comparing the feed-forward and feedback influences under varying degrees of situational familiarity (sessions) and under conditions of varying degrees of visual processing (eyes-closed, eyes-open, and video viewing), we presented evidence that the balance in θ - α band activity between the FF and FB influences is modulated by two factors. First, situational familiarity can reduce the degrees of θ and α dominance in the FB and FF influences, respectively (as in the case of eyes-closed). Second, the amount of sensory processing increases the θ band contribution and decreases α band contribution to FF influence but has little effect on FB influence. Finally, situational familiarity and sensory processing jointly determine the θ - α balance. Increasing familiarity and increasing visual processing both *increases* θ band contribution to *FF* influence. In contrast, for *FB* influences, increasing familiarity *decreases* θ band contribution when there is little demand for visual

processing (eyes-closed) and has no effect on θ band contribution when there is high demand for visual processing (visual).

Together, these findings demonstrate a novel non-invasive approach to the assessment of top-down and bottom-up influences in the human brain. These findings may particularly benefit those clinicians and researchers who are interested in how bottom-up and top-down influences interact in both diseased and normal brains. Future work will extend this analysis to networks involving more functionally distinct brain regions.

Acknowledgments. Supported by a grant from Sandia National Labs to A.C.T.

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