Anticipated synchronization in human EEG data: unidirectional causality with negative phase-lag

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Understanding the functional connectivity of the brain has become a major goal of neuroscience. In many situations the phase, together with coherence patterns, has been employed to infer the direction of the information flow. However, it has been recently shown in local field potential data from monkeys that the existence of a synchronized regime in which unidirectionally coupled areas can present both positive and negative phase differences. During the counterintuitive regime, called anticipated synchronization (AS), the phase difference does not reflect the causality. Here we investigate coherence and causality at the alpha frequency band (f \( \sim \) 10 Hz) between pairs of electroencephalogram (EEG) electrodes in humans during a GO/NO-GO task. We show that human EEG signals can exhibit anticipated synchronization, which is characterized by a unidirectional influence from an electrode A to an electrode B, but the electrode B leads the electrode A in time. To the best of our knowledge, this is the first verification of AS in EEG signals and in the human brain. The usual delayed synchronization (DS) regime is also present between many pairs. DS is characterized by a unidirectional influence from an electrode A to an electrode B and a positive phase difference between A and B which indicates that the electrode A leads the electrode B in time. Moreover, we show that EEG signals exhibit diversity in the phase relations: the pairs of electrodes can present in-phase, anti-phase, or out-of-phase synchronization with a similar distribution of positive and negative phase differences.

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Introduction

The extraordinary ability of humans to model and predict facts are one of the prerequisites for both action and cognition. These capacities emerge from the various synchronous rhythms generated by the brain [1, 2], which represent a core mechanism for neuronal communication [3]. In particular, phase synchronization [4] has been related to selective attention [5, 6], large-scale information integration [7] and memory processes [8, 9]. Despite huge evidence of zero-lag synchronization in the brain [2], there is a growing number of studies reporting non-zero phase differences between synchronized brain areas [6, 9, 10, 11, 12, 13]. It has been assumed that phase diversity plays an important role in fast cognitive processes [14].

In many situations the phase, together with coherence patterns, has been employed to infer the direction of the information flow [10, 15, 16, 17, 18, 19]. The assumption is typically that the phase difference reflects the transmission time of neural activity. However, this assumed relationship is not theoretically justified [20]. Particularly, during special synchronized regimes, the phase difference does not reflect the causality [21, 22, 23, 24, 25].

It has been shown that a monkey performing a cognitive task can present unidirectional influence from a cortical region A to another region B with a negative phase difference between the two areas [21, 22, 23]. This means that the receiver region B can lead the activity of A. For example, it has been observed that during the waiting period of a GO/NO-GO task, a macaque monkey present unidirectional causality from the somatosensory cortex to the motor cortex with a negative phase [21, 22]. A similar apparent incongruence has been verified between PreFrontal Cortex (PFC) and Posterior Parietal Cortex (PPC) in monkeys performing a working memory task [22]. The information flows from the PPC to the PFC but the activity of the PFC leads the activity of the PPC by 2.4 to 6.5 ms.

These experimental results have been compared to a model of two unidirectionally coupled neuronal popu-
The phase difference between the sender and the receiver population can be controlled by the inhibitory synaptic conductance in the receiver population or by the amount of external noise at the receiver. By construction, the information flow is always from the sender to the receiver population but the receiver can lead the sender, which is characterized by a negative phase difference. In other words, the sender lags behind the receiver. Results were corroborated using the statistical permutation quantifiers in the multi-scale entropy causality plane. This counter-intuitive regime has been explained in the light of anticipated synchronization (AS) ideas.

The anticipatory synchronization can be a stable solution of two dynamical systems coupled in a sender-receiver configuration, if the receiver is also subjected to a negative delayed self-feedback. In such system, the solution of the system, which can be easily verified by direct substitution in Eq. 1, is a solution of the system, which can be expressed as

\[ \dot{S} = f(S(t)), \]
\[ \dot{R} = f(R(t)) + K[S(t) - R(t - t_d)]. \]

Here we analyzed the 300 ms before the stimulus onset. Depending on the combination of stimuli, participants should press a button or not. Oscillatory main frequency, synchronized activity and directional influence were estimated by the power, coherence, phase difference and Granger causality spectra as reported in Matias et al. (see more details in Sec. III).

FIG. 1: Experimental paradigm. (a) 10/20 System of EEG electrodes placement employed in the experiments. (b) GO/NO-GO task based on three types of stimulus with images of animals (A), plants (P), and people (H). Here we analyzed the 300 ms before the stimulus onset.

Synchronization between electrodes \( l \) and \( k \) can be characterized by a peak in the coherence spectrum \( C_{lk}(f_{peak}) \). The phase difference \( \Delta \Phi_{l-k} \) at the peak frequency \( f_{peak} \) provides the time delay \( \tau_{lk} \) between the electrodes. The direction of influence is given by the Granger causality spectrum. Whenever an electrode \( l \) strongly and asymmetrically \( G \)-causes \( k \), we refer to \( l \) as the sender (S) and to \( k \) as the receiver (R) and the link between \( l \) and \( k \) is considered a unidirectional coupling from \( l \) to \( k \) (S \( \rightarrow \) R). After determining which electrode is the sender and which one is the receiver we analyze the sign of \( \Delta \Phi_{S-R} \) to determine the synchronized regime.
FIG. 2: Unidirectional causality with positive phase-lag characterizes the delayed synchronization regime (DS). Power, coherence, Granger causality and phase spectra between electrodes $F_7$ and $F_{P1}$ for volunteer 439. The pair is synchronized with main frequency $f_{\text{peak}} = 11.4$ Hz (given by the peak of the coherence, grey dashed lines). The Granger causality peak around $f_{\text{peak}}$ reveals a directional influence from site $F_7$ to $F_{P1}$ and the phase difference at the main frequency $\Delta \Phi_{F_7-F_{P1}}(f_{\text{peak}}) = 0.1727$ rad shows that $F_7$ leads $F_{P1}$ (with an equivalent time delay $\tau = 2.4$ ms).

Unless otherwise stated we analyze only the unidirectionally connected pairs.

Delayed synchronization (DS): unidirectional causality with positive phase-lag

Typically when a directional influence is verified from A to B, a positive time delay is expected, indicating that A’s activity temporally precedes that of B [10, 54]. This positive time delay characterizes the intuitive regime called delayed synchronization (DS, or also retarded synchronization) in which the sender is also the leader [23]. In neuronal models the time delay between A and B can reflect the characteristic time scale of the synapses between A and B but can also be modulated by local properties of the receiver region B [23, 24].

In Fig. 2 we show an example of DS between the sites $F_7$ and $F_{P1}$ for volunteer 439. Power and coherence spectra present a peak at $f_{\text{peak}} = 11.4$ Hz. At this frequency, the activity of $F_7$ G-causes $F_{P1}$, but not the other way around. The positive sign of the phase $\Delta \Phi_{F_7-F_{P1}}(f_{\text{peak}}) = 0.1727$ rad indicates that the sender electrode $F_7$ leads the receiver electrode $F_{P1}$ with a positive time delay $\tau = 2.4$ ms.

Anticipated synchronization (AS): unidirectional causality with negative phase-lag

Despite the fact that phase differences and coherence patterns, have been employed to infer the direction of the information flux [10, 12, 16, 17, 18, 19], our results imply that if we consider only the coherence and phase-lag we could infer the wrong direction of influence between the involved pairs. Such counter-intuitive regime exhibiting unidirectionally causality with negative phase difference has first been reported in the brain as a mismatch between causality and the sign of the phase difference in local field potential of macaque monkeys during cognitive tasks [21, 22]. Afterwards, it has been reported that the apparent paradox could be explained in the light of anticipated synchronization ideas [23]. Here we show that human EEG signals can also present unidirectional influence with negative phase-lag. As far as we know, this is the first evidence of AS in human EEG data.

An example of anticipated synchronization between EEG electrodes is shown in Fig. 3. The sites $F_Z$ and $F_{P1}$ exhibit a peak at alpha band in the power and coherence spectra for $f_{\text{peak}} = 10.8$ Hz (Fig. 3) for volunteer 439. The Granger causality spectra presents a peak from $F_Z$ to $F_{P1}$ but not in the opposite direction, indicating that $F_Z$ G-causes $F_{P1}$ at $f_{\text{peak}} = 10.8$ Hz. However, the negative sign of the angle $\Delta \Phi_{F_Z-F_{P1}}(f_{\text{peak}}) = -0.1969$ rad indicates that the activity of $F_Z$ lags behind the activity of $F_{P1}$. The time delay associated to $\Delta \Phi_{F_Z-F_{P1}}(f_{\text{peak}})$ is $\tau = -2.9$ ms.

It is worth mentioning that for linear phase responses, which is the case for a simple monochromatic sinusoidal function, the phase delay and the group delay (defined by the derivative of phase with respect to frequency) are identical. In this case, both phase and group delays may be interpreted as the actual time delay between the signals. For time series that are synchronized in a broad
frequency band, the group delay could be useful to estimate the time difference between the signals. Indeed, a negative group delay has been associated with anticipatory dynamics [55, 56, 57] and it is comparable to the time difference obtained by the cross-correlation function [55]. Here, we verified that some AS pairs present both negative phase delay and negative group delay (as in the example shown in Fig. 3). However, this is not the case for all AS pairs in the analyzed data. We have found all possible combinations for the signs of phase and group delays for both DS and AS. A further investigation of the relation between phase delay and group delay in brain signals is out of the scope of this paper and should be done elsewhere.

Zero-lag synchronization (ZL)

Zero-lag (ZL) synchronization has been widely documented in experimental data since its first report in the cat visual cortex [58]. It has been related to different cognitive functions such as perceptual integration and the execution of coordinated motor behaviours [3, 7, 55, 60]. Despite many models showing that bidirectional coupling between areas promotes zero-lag synchronization [61, 62], it is also possible to have ZL between unidirectional connected populations [23, 26, 34]. In these systems, nonlinear properties of the receiver region can compensate characteristic synaptics delays and the two systems synchronize at zero phase.

We consider zero-lag whenever $|\Delta \Phi_{S\rightarrow R}(f_{\text{peak}})| < 0.1$. In Fig. 4 we show power, coherence, Granger causality and phase spectra between electrodes $F_3$ and $F_{P2}$ for volunteer 439. These sites are synchronized with main frequency $f_{\text{peak}} = 10.4$ Hz and $\Delta \Phi_{F_3\rightarrow F_{P2}}(f_{\text{peak}}) = -0.0164$ rad which provides $\tau = -0.2$ ms.

Anti-phase synchronization

Participants can also exhibit anti-phase synchronization between electrodes. We define anti-phase synchronization (AP) when $\pi - 0.1 < |\Delta \Phi_{S\rightarrow R}(f_{\text{peak}})| < \pi + 0.1$ rad. In Fig. 5 we show power, coherence, Granger causality and phase spectra between electrodes $O_2$ and $C_3$ for volunteer 439. The site $O_2$ G-causes $C_3$ and the time delay between them is $\tau = 47.5$ ms which is almost half of a period for the $f_{\text{peak}} = 10.4$ Hz.

| TABLE I: Number of unidirectionally connected pairs for all subjects together: separated by phase-synchronization regime along the lines and by the direction of influence along the columns. |
|---|---|---|---|---|
| | Unidirectional | Back-to-Front | Lateral | Front-to-Back |
| Total | 686 | 430 | 90 | 166 |
| ZL | 93 | 39 | 25 | 29 |
| DS(1) | 77 | 25 | 14 | 38 |
| AS(1) | 99 | 51 | 27 | 21 |
| AP | 174 | 135 | 11 | 28 |
| DS(2) | 108 | 83 | 4 | 21 |
| AS(2) | 135 | 97 | 9 | 29 |
FIG. 4: **Unidirectional causality with zero-lag synchronization (ZL, defined by $\Delta \Phi \simeq 0$).** Power, coherence, Granger causality and phase spectra between electrodes $F_3$ and $F_{P2}$ for volunteer 439. Sites are synchronized with main frequency (given by the peak of the coherence, brown dashed lines) $f_{\text{peak}} = 10.4$ Hz. The Granger causality peak around $f_{\text{peak}}$ indicates that site $F_3$ unidirectionally influences $F_{P2}$. The time delay between both is almost zero $\tau = -0.2\,\text{ms}$ ($\Delta \Phi_{F_3 - F_{P2}}(f_{\text{peak}}) = -0.0164$ rad).

FIG. 5: **Unidirectional causality with anti-phase synchronization (AP, defined by $\Delta \Phi \simeq \pm \pi$).** Power, coherence, Granger causality and phase spectra between electrodes $O_2$ and $C_3$ for volunteer 439. The activity of the electrodes are synchronized with main frequency $f_{\text{peak}} = 10.4$ Hz (grey dashed lines). The Granger causality peak around $f_{\text{peak}}$ reveals a directional influence from $O_2$ to $C_3$ and the phase spectrum shows that $\Delta \Phi_{O_2 - C_3}(f_{\text{peak}}) = 3.1031$ rad (which provides $\tau = 47.5\,\text{ms}$).

**Phase relation diversity across pairs and subjects**

Reliable phase relation diversity is a general property of brain oscillations. It has been reported on multiple spatial scales, ranging from very small spatial scale (inter-electrode distance $< 900$ mm) in macaque $\text{C}$ to a large spatial scale (using magnetoencephalography)
in humans [14]. However, the functional significance of phase relations in neuronal signals is not well defined. It has been hypothesized that it may support effective neuronal communication by enhancing neuronal selectivity and promoting segregation of multiple information streams [14].

Considering the 19 electrodes per subject, the number of analyzed pairs is 171 for each volunteer which corresponds to 1881 pairs in total. Among these pairs, 1394 presented a peak in the coherence spectrum at the alpha band. Regarding the Granger causality spectra, 686 pairs presented a unidirectional influence and 358 a bidirectional influence. In Fig. 6(a) we show the phase-difference distribution of all 686 unidirectionally connected pairs for all volunteers in a circular plot. In Figs. 6(b),(c),(d) we show all the pairs separated by the direction of influence: all unidirectional pairs, back-to-front influence, front-to-back influence, lateral and front-to-back direction. (b) All unidirectional pairs separated per volunteer.

The total number of synchronized and unidirectionally connected pairs varies among volunteers, as well as the distribution of phases. All subjects present DS, AS, ZL and AP pairs (see Fig. 7(b)). However, one subject does not present AS(1). All subjects present back-to-front, lateral and front-to-back influence and more pairs with back-to-front than front-to-back direction of influence. Considering only the back-to-front pairs, there are more AP than ZL synchronized regimes. This is also true if we compare all pairs in the second and third quadrant (AP, DS(2) and AS(2)) with the ones in the first and fourth (ZL, DS(1), AS(1)).

As illustrative examples, in Fig. 8 we show the direction of influence between some pairs that have the same unidirectional back-to-front Granger for at least 4 subjects and their respective phases. Almost all pairs that have the electrodes $P_2$, $P_3$ and $P_4$ as the sender present phases close to anti-phase (AP, DS(2), AS(2)), whereas almost all the pairs in which the sender is $F_2$, $T_3$ or $T_4$ are synchronized close to zero-lag (ZL, DS(1), AS(1)).

Regarding back-to-front influences, no pair presented the same Granger causal relation for 9 or more subjects. Three pairs exhibited same unidirectional relation for 8 volunteers: $P_2 \rightarrow F_2$, $P_3 \rightarrow F_4$, $O_1 \rightarrow F_2$; other 3 pairs presented the same unidirectional relation for 7 subjects:

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$P_3 \rightarrow F_4$, $P_3 \rightarrow F_8$, $O_1 \rightarrow F_{P2}$. Ten pairs had same Granger causal relation for 6 volunteers: $F_Z \rightarrow F_{P1}$, $P_3 \rightarrow F_{P1}$, $P_3 \rightarrow F_3$, $C_2 \rightarrow F_8$, $C_Z \rightarrow T_3$, $C_4 \rightarrow F_{P1}$, $C_4 \rightarrow F_7$, $C_4 \rightarrow F_3$, $O_1 \rightarrow F_{P1}$, $O_2 \rightarrow F_4$. All these 16 pairs had none or only one other subject presenting the opposite direction of the Granger causality. Out of these 16 pairs, only $F_Z \rightarrow F_{P1}$ is mostly synchronized close do ZL as shown in Figs. 8(a) and (b), all others are mostly synchronized close to AP as in Figs. 8(c)-(f).

![Image](image.png)

FIG. 8: Illustrative examples of unidirectionally connected pairs and their phase relations. (a) and (b) Example of pairs with the majority of phase differences in the first and the fourth quadrants (ZL, DS(1), AS(1)): $F_Z \rightarrow F_{P1}$, $F_Z \rightarrow F_{P2}$, $T_3 \rightarrow F_{P1}$ and $T_4 \rightarrow F_{P2}$. (c) to (f) Example of pairs with the majority of phase differences in the second and the third quadrants (AP, DS(2), AS(2)). $P_Z$, $P_3$ and $P_4$ are well connected senders. All the chosen pairs are synchronized with same direction of influence for at least 4 subjects.

II. CONCLUSION

We show that human EEG can simultaneously present unidirectional causality and diverse phase relations between electrodes. Our findings suggest that the human brain can operate in a dynamical regime where the information flow and relative phase-lag have opposite signs. To the best of our knowledge this is the first evidence of unidirectional influence accompanied by negative phase differences in EEG data. This counter-intuitive phenomena have been previously reported as anticipated synchronization in monkey LFP [21, 22, 23], in neuronal models [34, 35, 41, 43, 44] and in physical systems [36, 37, 38, 39, 40]. Therefore, we propose that this is the first verification of anticipated synchronization in EEG signals and in human brains.

Studies estimating the actual brain connectivity using data from EEG signals should consider many relevant issues such as [64]: the importance of common reference in EEG to estimate phase differences [20] and the effects of volume conduction for source localization [65, 66]. Our findings suggest that it is also important to take into account the possible existence of AS in connectivity studies and separately analyze causality and phase relations. It is worth mentioning that, it has been shown that for enough data points the Granger causality is able to distinguish AS and DS regimes [24]. However, for very well behaved time series the reconstruction of the connectivity can be confused by the phase [22].

Our results open important avenues for investigating how neural oscillations contribute to the neural implementation of cognition and behavior as well as for studying the functional significance of phase diversity [6, 14]. Future works could investigate the relation between anticipated synchronization in brain signals and anticipatory behaviors such as anticipation in human-machine interaction [52] and during synchronized rhythmic action [53]. It is also possible to explore the relation between consistent phase differences and behavioral data such as learning rate, reaction time and task performance during different cognitive tasks. Neuronal models have shown that spike-timing dependent plasticity and the DS-AS transition together could determine the phase differences between cortical-like populations [42]. However, an experimental evidence for the relation between learning and negative phase differences is still lacking.

We also suggest that our study can be potentially interesting to future researches on the relation between inhibitory coupling, oscillations and communication between brain areas. On one hand, inhibition is considered to play an important role to establish the oscillatory alpha activity, in particular, allowing selective information processes [67]. On the other hand, according to the anticipated synchronization in neuronal populations model presented in Ref. [23], a modification of the inhibitory synaptic conductance at the receiver population can modulate the phase relation between sender and receiver, eventually promoting a transition from DS to AS. Therefore, we suggest that the inhibition at the receiver region can control the phase difference between cortical areas, which has been hypothesized to control the efficiency of the information exchange between these areas, via communication through coherence [6, 14].
III. APPENDIX: METHODS

Subjects

We analyzed data from 11 volunteers (10 women, 1 man, all right-handed) who signed to indicate informed consent to participate in the experiment. The youngest was 32 years old and the oldest 55 years old (average 45.7 and standard deviation 7.8). All subjects were evaluated by both psychiatrist and psychologist. Exclusion criteria were: perinatal problems, cranial injuries with loss of consciousness and neurological deficit, history of seizures, medication or other drugs 24 hours before the recording, presence of psychotic symptoms in 6 months prior the study and the presence of systemic and neurological diseases. The experiment was not specifically designed to investigate the phenomena of anticipated synchronization in humans and the data analyzed here were first analyzed in Ref. [68]. The entire experimental protocol was approved by the Commission of Bioethics of the University of Murcia (UMU, project: Subtipos electrofisiológicos y mediante estimulación eléctrica transcranial del Trastorno por Dificil de Atención con o sin Hiperalactividad).

EEG recording

The electroencephalographic data recordings were carried out at the Spanish Foundation for Neurometrics Development (Murcia, Spain) center using a Mitsar 201M amplifier (Mitsar Ltd), a system of 19 channels with auricular reference. Data were digitized at a frequency of 250 Hz. The electrodes were positioned according to the international 10-20 system using conductive paste (ECI ELECTROGEL). Electrode impedance was kept < 5 KΩ. The montage (Fig. 1(a)) include three midline sites (FZ, C2 and P2) and eight sites over each hemisphere (FP1/FP2, P7/F8, F3/F4, T3/T4, C3/C4, P3/P4, T5/T6 and O1/O2). The acquisition was realized with WinEEG software (Version 2.92.56). EEG epochs with excessive amplitude (> 50 µV) were automatically deleted. Finally, the EEG was analyzed by a specialist in neurophysiology to reject epochs with artifacts.

Experimental task

The EEG data were recorded while subjects performed a GO/NO-GO task (also called visual continuous performance task, VCPT). Participants sat in an ergonomic chair 1.5 meters away from a 17” plasma screen. Psych task software (Mitsar Systems) was used to present the images. The VCPT consists of three types of stimuli: twenty images of animals (A), twenty images of plants (P), twenty images of people of different professions (H+). Whenever H+ was presented, a 20 ms-long artificial sound tone frequency was simultaneously produced. The tone frequencies range from 500 to 2500 Hz, in intervals of 500 Hz. All stimuli were of equal size and brightness.

In each trial a pair of stimuli were presented after a waiting window of 300 ms, which is the important interval for our analysis (see the green arrow in Fig. 1(b)). Each stimulus remains on the screen for 100 ms, with a 1000 ms inter-stimulus-interval. Four different kinds of pairs of stimuli were employed: AA, AP, PP and PH+. The entire experiment consists in 400 trials (the four kinds of pairs were randomly distributed and each one appeared 100 times). The continuous set occurs when A is presented as the first stimulus, so the subject needed to prepare to respond. An AA pair corresponds to a GO task and the participants are supposed to press a button as quickly as possible. An AP pair corresponds to a NO-GO task and the participants should suppress the action of pressing the button. The discontinuous set, in which P is first presented, indicates that one should not respond (independently of the second stimuli). IGNORE task occurred with PP pairs and NOVEL when PH+ pairs appeared. Participants were trained for about five minutes before beginning the experimental trials. They rested for a few minutes when they reached the halfway point of the task. The experimental session lasted ~ 30 min.

EEG processing and analysis

The Power, Coherence, Granger causality and phase difference spectra were calculated following the methodology reported in Matias et al. [23] using the autoregressive modeling method (MVAR) implemented in the MVGC Matlab toolbox [69]. Data were acquired while participants were performing the GO/NO-GO visual pattern discrimination described before. Our analysis focuses on 30000 points representing the waiting window of 400 trials ending with the visual stimulus onset (green arrow in Fig. 1(b)). This means that in each trial, the 300 ms pre-stimulus interval consists of 75 points with a 250-Hz sample rate.

The preprocess of the multi-trial EEG time series consists in detrending, demeaning and normalization of each trial. Respectively, it means to subtract from the time series the best-fitting line, the ensemble mean and divide it by the temporal standard deviation. After these processes each single trial can be considered as produced from a zero-mean stochastic process. In order to determine an optimal order for the MVAR model we obtained the minimum of the Akaike Information Criterion (AIC) [70] as a function of model order. The AIC dropped monotonically with increasing model order up to 30.

For each pair of sites (l, k) we calculated the spectral matrix element \( S_{lk}(f) \) [21, 71], from which the coherence spectrum \( C_{lk}(f) = |S_{lk}^2/S_{ll}(f)S_{kk}(f)| \) and the phase spectrum \( \Delta \Phi_{l-k}(f) = \tan^{-1}[\text{Im}(S_{lk})/\text{Re}(S_{lk})] \) were cal-
Directional influence from site $I$ via the Granger causality spectrum (Fig. 1(a)): back influence we separated the electrodes in 5 lines (see $C_{I}$ from the coherence spectrum, we consider that $l$ G-causes $k$. In order to define back-to-front, lateral or front-to-back influence we separated the electrodes in 5 lines (see Fig. II(a)): $F_{P1}$ and $F_{P2}$; $F_{7}, F_{3}, F_{Z}, F_{4}$ and $F_{8}$; $T_{3}, C_{3}$, $C_{Z}, C_{4}$ and $T_{4}$; $T_{5}$, $P_{3}$, $P_{Z}$, $P_{4}$, and $T_{6}$; $O_{1}$ and $O_{2}$.

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