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Long-distance neural synchrony correlates with processing strategies to compare fractions

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HIGHLIGHTS

- Long-distance neural synchrony modulated by fraction processing strategies.
- Alpha phase desynchronization induced by componential processing strategy.
- Theta and Gamma phase synchronization induced by holistic processing strategy.
- Holistic processing strategy evoked right anterior negativity around 400 ms.
- Early theta phase synchrony correlate with anterior negativity around 400 ms.

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ABSTRACT

Adults use different processing strategies to work with fractions. Depending on task requirements, they may analyze the fraction components separately (componential processing strategy, CPS) or consider the fraction as a whole (holistic processing strategy, HPS). It is so far unknown what is the brain coordination dynamics underlying these types of fraction processing strategies. To elucidate this issue, we analyzed oscillatory brain activity during a fraction comparison task, presenting pairs of fractions either with or without common components. Results show that CPS induces a left frontal-parietal alpha phase desynchronization after the onset of fraction pairs, while HPS induces an increase of phase synchrony on theta and gamma bands, over frontal and central-parietal sites, respectively. Additionally, the HPS evokes more negative ERPs around 400 ms over the right frontal scalp than the CPS. This ERP activity correlates with the increase of Theta phase synchrony. Our results reveal the emergence of different functional neural networks depending on the kind of cognitive strategy used for processing fractions.

1. Introduction

Recent research has demonstrated that educated adults use different strategies to solve problems involving fractions: in some contexts, adults consider only the fractions' numerators and denominators [1], whereas in other contexts they give signs of accessing the fractions' numerical magnitudes [2]. The adult brain seems to select between strategies based on isolated fraction components (componential processing strategies, CPS) and strategies based on the numerical fraction magnitude (holistic processing strategies, HPS) depending on task demands [1]. In the case of fraction comparison, the CPS is favored when the fractions to be compared share a common component (e.g., 1/4 vs. 1/9 or 2/6 vs. 3/6) [1], whereas the HPS is preferred when the fractions lack common components (e.g., 5/9 vs. 6/8 or 3/6 vs. 2/5) [2].

To date, few studies have investigated the brain correlates of these processing strategies. A recent ERP study [3] showed that the use of the CPS while comparing fractions of the form $1/n$ to the standard 1/5 elicits a P3 component, whose latency grows if the stimulus set to compare to 1/5 comprises both fractions and decimals (e.g., 1/3, 0.2). This mixed condition also evoked an N2 component over frontal electrodes, probably reflecting higher cognitive demands [3]. In addition, a functional magnetic resonance study [4] has investigated the brain areas involved in fraction comparison and found that whereas both the CPS and the HPS activate frontoparietal regions, only the HPS modulates activity in the intraparietal sulcus, a region traditionally associated with the mental representation of numerical magnitude [5].

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Although ERPs provide fine-grained information about the time course of fraction processing strategies and the fMRI data indicate what are the relevant brain structures associated to these processes, the oscillatory dynamics of the neural networks involved may provide us with additional valuable information about the mechanisms underlying the processing of fractions. In this article, we analyze local and long-distance neuronal synchrony activity [6], which are well-established ways to investigate the dynamics of functional network formation during cognitive information processing [7–9]. There are many ways of quantifying neural synchrony. Here we focus on two of them: The first one is induced spectral power analysis, or amplitude variations in EEG oscillatory activity [10]. This measure is a good indicator of synchronization of large groups of neurons located in the same brain region [11]. The second analysis measures phase coupling, that is to say the relative stability of the difference of phases between pairs of electrodes [6]. High values of phase coupling between two electrodes suggest that large groups of neurons far from each other are functionally related [6]. Thus, induced spectral power and phase synchrony provide us with two measures containing different, but complementary, information.

In the present study we explore the local and long-distance neural synchronization correlates of the CPS and the HPS in the processing of fractions. Additionally, we analyze ERPs for comparison with previous results [3]. We recorded EEG signals in subjects engaged in a fraction comparison task. To elicit preferentially either the CPS or the HPS, we presented pairs of fractions with and without common components, respectively [4]. As indicators of local and long-distance neural coordination, we measured over a wide frequency range the induced spectral power of local signals [10] and the phase synchronization across recording sites [6,12]. We found that CPS and HPS differ with respect to global synchronization and ERP, but not to local neural processing. We propose that long-distance neural integration is the critical event that mediates the efficient allocation of cognitive resources during processing of fractions.

2. Methods

2.1. Subjects

Twenty subjects (11 males, age range: 18–41 years, mean age = 28.4 years) participated in an EEG experiment. Five subjects were excluded from the analysis because they presented less than 50 percent of artifact-free EEG trials per experimental condition (total trials per condition = 78; mean artifact-free trials: CPS = 67.9, HPS = 62.4). All participants were native Spanish speakers, right handed, with normal hearing and normal or corrected to normal vision, and with no history of neurological and/or psychiatric illness. The Ethical Committee of the Medicine Faculty of the University of Chile approved the protocols used in this study, and all participants gave written informed consent before being tested.

2.2. Stimuli

We used 156 different pairs of fractions with single-digit numerators and denominators in a fraction comparison task. All numerators and denominators were in the range 1–9, such that the resulting fractions were always proper. Fractions were presented as two vertically displaced digits separated by a horizontal line and displayed in silver color on a black background. Each fraction measured 1.5 cm × 5.5 cm (width × height). Fractions were located 2 cm to the left or right of the center of the screen. Viewing distance was 63 ± 3 cm.

We grouped fraction pairs into two blocks of trials to better study the CPS and HPS, as suggested previously [4]. In the CPS block, fraction pairs had a common component (either a common numerator, e.g. 1/6 and 1/8, or a common denominator, e.g. 2/7 and 4/7), whereas in the HPS block, fraction pairs had no common component (e.g. 3/7 and 2/9). Each block consisted of 78 pairs of fractions. Within each block, the order of presentation of fraction pairs was pseudo-random. The order of presentation of the two blocks was counterbalanced between subjects.

2.3. Procedure

Prior to the experiment, participants read the instructions for the fraction comparison task. Each experimental trial began with the presentation of a fixation cross in the center of the screen (duration between 1500 and 2400 ms), followed by the visual presentation of the fraction pair (3000 ms), and finally by a question mark that appeared on the screen as a cue for subjects to respond. In this period, subjects indicated which one of the two fractions was the largest by pressing one of two possible response buttons. The question mark remained on the screen until the subject pressed a button.

EEG recording was performed inside a Faraday cage. The fraction comparison task was programmed with the stimulus presentation software E-Prime version 2.0. The pairs of fractions were presented visually in the center of a PC monitor screen and behavioral responses were collected with a response pad EGI 200.

2.4. Data analysis

EEG activity was recorded with 64-sensor HydroCel GSN nets referenced to vertex (Electrical geodesics, Eugene, OR, USA). The EEG was filtered online from 0.01 to 100 Hz in order to eliminate DC fluctuations, and digitized at 1000 Hz. Electrode impedances were below 40 kΩ, the optimal level for this system [13]. Finally, the signal was stored for offline analysis.

2.4.1. Induced spectral power and phase synchrony

The raw EEG signal was first segmented into a series of epochs lasting 3400 ms including 1200 ms preceding the onset of the fraction pair, and then re-referenced off-line to average reference. Electrodes placed near the eyes and face were excluded from analysis. Thus, we estimated phase synchrony for 59 out of 64 channels. The continuous 50 Hz (AC) components were filtered in each epoch with a zero-phase filter that keeps the biological 50 Hz signal. Trials containing voltage fluctuations that exceeded ±200 μV or transients exceeding ±100 μV were excluded from analysis.

The artifact-free signal was then processed with a sliding-window fast Fourier transform (window length, 256 ms; step, 10 ms). By this process we obtained amplitude and phase values for frequencies between 1 and 90 Hz with 1 Hz frequency resolution. Then, amplitude information was used to compute the induced spectral power that is obtained by averaging the time-frequency energy across single trials (see [10] for details), while the phase information was used to obtain the phase-locking value (PLV) [12]. In brief, this method involves computing the phase difference in a time window for each electrode pair and assessing the stability of such phase difference through all trials and all different frequencies in the EEG.

The charts of induced spectral power and phase synchronization were normalized to a baseline period starting 400 ms before the onset of the fraction pair. We normalized the signal by subtracting the average activity of the baseline from the raw signal and then dividing by the standard deviation of the baseline, in a frequency-by-frequency manner.