Inter-brain Mutual Information in Social Interaction Tasks

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Abstract— **Using a dual EEG set-up, pairs of subjects jointly performed finger movement tasks under three conditions: *intrinsic*- ignore; *in-phase* - follow; and *anti-phase* - oppose their partner's movement patterns. Group ICA was employed for signal decomposition in the 10-12 Hz range. Mutual information across dyads was estimated in tasks relative to baseline. Results demonstrated information encoding (between partners) in the anti-phase was two times more than the intrinsic which in turn expressed twice as much information content as the more automatic in-phase task. Topography of significant components revealed involvement of the frontal brain region in the intrinsic; both frontal and occipital brain regions in anti-phase suggesting decision making and employment of visual resources in these tasks.**

Keywords- Independent component analysisn (ICA); Mutual information (I); Social interaction

I. INTRODUCTION

Social interactions rely upon mutual information exchange where one's behaviour change in response to the other yet at the same time modifies theirs. Previous research has demonstrated specific and differential modulations of upper mu (10-12 Hz) ERD/S [6] pre-dominantly at centro-parietal locations in various modes of dyadic social interaction [1, 2]. These signatures were strongly suggestive of the employment of cognitive factors embedded in the different intentions of the tasks [2]. However, relative contributions of intent in coordinated behaviors cannot be ascertained at least in part because analysis was confined to within individual subjects/brains. Clearly, an important next step is direct inter-brain analysis which might bring forth new aspects of brain-to-brain coupling in dyadic social interactions [8, 9, 10, 11].

The present work, though preliminary is a step in this direction. For this purpose information theoretic methods were used. First, signals were decomposed by employing group independent component analysis (ICA) [3]. Next, mutual information concepts [4] and tools [7] were utilized to quantify the relative coding strengths of different tasks (vis-à-vis base-line). The ICA algorithm used here is based on the infomax principle which achieves source separation by minimizing mutual information between components [5]. In other words it aims to construct new independent time courses each depicting the maximum possible redundancy of information. As a consequence, if a task is different from baseline, simultaneous decomposition of the two should yield distinct ICA components. If a task has more information content relative to baseline, ICA decomposed signals should express increased mutual information.

This consistent information-theoretic approach of ICA decomposition in conjunction with mutual information analysis--which quantifies the mutual dependence between random variables [4]—is presented in this manuscript to decipher the coding capacity of tasks in specific brain regions.

II. MATERIALS AND METHODS

Twelve normal healthy subjects (mean age 30 years +/- 6.5 years) forming six pairs were instructed to interact in a simple motor task in three different interaction scenarios. Both finger movement and EEG data were recorded [11, 12].

60 channels of EEG were collected at the same time on both dyad members following the 10% system, mounted on whole head elasticated electrode caps [11, 12]. Experimental trials consisted of a 'baseline' segment followed by one of the 'active' coordination scenarios. During the baseline a partner's actions were deliberately obscured from the field of view whereas in active segments dyads were instructed to visually couple their movement patterns according to task instructions. The following tasks were performed: Intrinsic (I) where both subjects were required to produce their own movements at their preferred frequency and amplitude while ignoring their partner's self-paced movements; In-phase (*Ip*) where partners were required to synchronize their finger
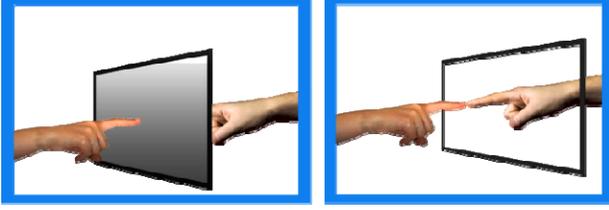
Figure 1 Left: No-vision baseline period. Right: Vision task period. Each period is 20 s duration.

movements; and <u>Anti-phase</u> (*Ap*) where partners were required to syncopate with each other (Figure 1). Total trial length was 40 s with baseline and active segments contributing 20 s each. Multiple trials were collected for each baseline/active pairing for each dyad in a random order. Full details of the experimental design and behavioural analysis are published elsewhere [1, 2].

EEG signals of each subject and task were filtered (bi-directional in the range 10-12 Hz). Data of all subjects were co-joined/concatenated and separate Group ICA [3] was performed for each task. This yielded 60 components in each task as no dimensional reduction was employed. Notably, ICA weights are learned on base-line as well as active period for respective tasks.

Mutual information [4] measures how many bits of information random variable X and Y share:

$$I(X; Y) = H(X) + H(Y) - H(X, Y)$$

where $H(X)$ and $H(Y)$ are the marginal entropies and $H(X, Y)$ the joint entropy of X and Y. In the present context these quantities represent the EEG signals of the dyads. Mutual information was estimated for each component across subject pairs, separately for base-line and active periods in each trial of each task. This process was repeated by employing the ICA unmixing matrix estimated separately for the three tasks. The algorithm utilized for the estimation of mutual information is available in EEGLAB [7]. Default 100 bins were utilized for data quantization. The relative mutual information for pairs, components and trials was estimated as:

$$\Delta I = I_{active} - I_{baseline}$$

A repeated measures analysis of variance (ANOVA) was performed (separately for each task) to investigate the effects of social interaction as measured by relative mutual information across components. All 60 components were used as factors. Post-hoc was performed using 1-sample t-tests to determine which components exhibited *increased* mutual information.
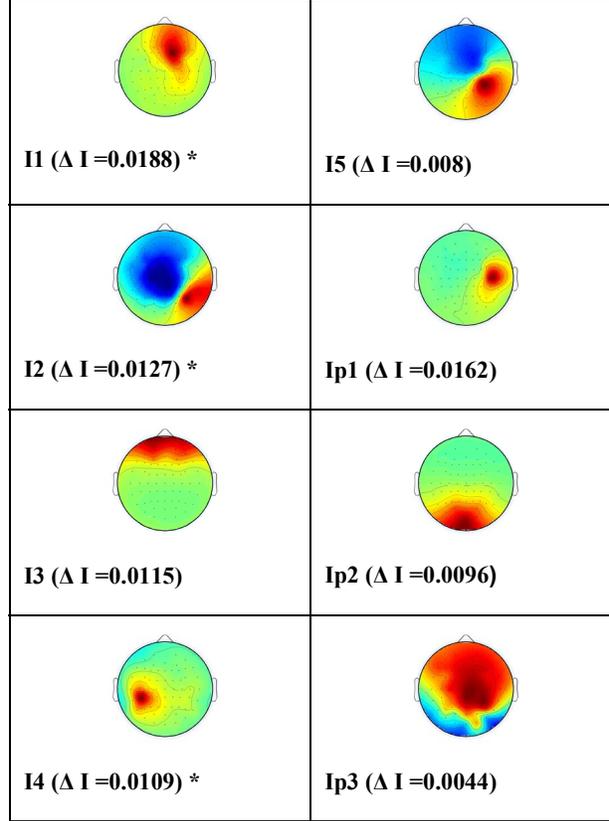

Figure 2 Statistically significant components of intrinsic task (*). Some other components of intrinsic and in-phase are also shown. Numerical values depict relative mutual information in bits.

III. RESULTS

A one-way ANOVA revealed significant differences in ΔI across components in the case of intrinsic [$F_{(59, 295)} = 1.52$, $p < 0.05$] and anti-phase [$F_{(59, 295)} = 1.64$, $p < 0.005$] clearly indicating that at least a hand full of components are specifically task-related.

To further investigate which components are significant post-hoc 1-sample t-tests (p, 0.05) were conducted. This analysis revealed increased frontal involvement among dyads in the intrinsic task. Notably, frontal components (especially I1) showed a strong increase in mutual information (Figure 2). Moreover, the presence of two bipolar components suggests an interesting connection between frontal and centro-parietal regions (see I2 and I5). On the other hand, the anti-phase task showed marked employment of vision related processes: a number of components depicting occipital and parieto-occipital topography exhibited a strong increase in mutual information (Figure 3- see Ap2, Ap4, Ap5). Additionally, the presence of two strong frontal components (especially Ap1) implicates

cognitive factors as well in this mode of social interaction. In contrast, the in-phase task depicted no statistically significant effects in a 1-way ANOVA.

The total relative mutual information across all components, pairs and trials may shed further on effects of social interaction tasks in line with previous work [1, 2] as well as the analysis presented here. The estimated global means are shown in Figure 4. Here an interesting picture emerges. Comparatively speaking, it can be seen that the most information exchange between dyads relative to baseline occurs in the anti-phase task, followed by intrinsic and in-phase task conditions. Indeed, taken on face value, modulations in intrinsic and anti-phase caused twice and 4 time as much information encoding among dyads as in-phase. Also, the number of components in the anti-phase and to a lesser the intrinsic condition showed substantially increased mutual information- a fact that is in contrast with in-phase. In general, the present information theoretic approach could not differentiate in-phase from baseline activity whereas other two tasks have been shown to employ task specific processes.
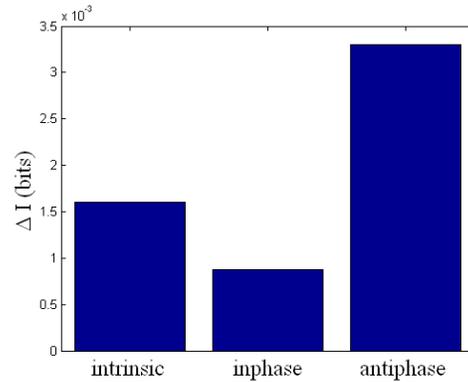

Figure 4 Gross relative mutual information in tasks: Intrinsic (0.00160), In-phase (0.00087) and Anti-phase (0.00330).

IV. DISCUSSION

Behavioural collaboration and interaction in social environments is an important feature of group functioning in human society. The methodological and analytic approach adopted here represents a novel way to develop a better understanding of how the dynamics of such interactions unfold and how they are determined by the properties of the interaction.

Our results confirm that even in simple motor interaction scenarios, properties of an interaction state or intent modulate mutual information transfer between those participating in the interaction. In the in-phase condition we found no evidence of a marked change in mutual information during task engagement compared to baseline. This finding is consistent with previous work which reports that imitation of motor acts and gestures during social interaction is the natural and perhaps automatic response between individuals in such situations. Therefore harmonization of behavior is the natural default and may require little additional conscious intervention to modify automatic responses. This situation contrasts markedly with the other two task conditions however. In the Intrinsic task for example ICA identified an enhancement of a component related to frontal engagement and an increase in the mutual information between dyad partners. This is taken to indicate increased top-down information processing load and increased need for transfer of information between the subjects to maintain the task setting. In this respect more information about the properties of each partner's actions is required to maintain alignment with task instructions: mutual information exchange here is based on the fact that the partners must in actuality override their natural inclination to duplicate each other's motor behavior. ICA and mutual information changes are even more marked in the anti-phase task situation. Here specific ICA components are identified related to both frontal and
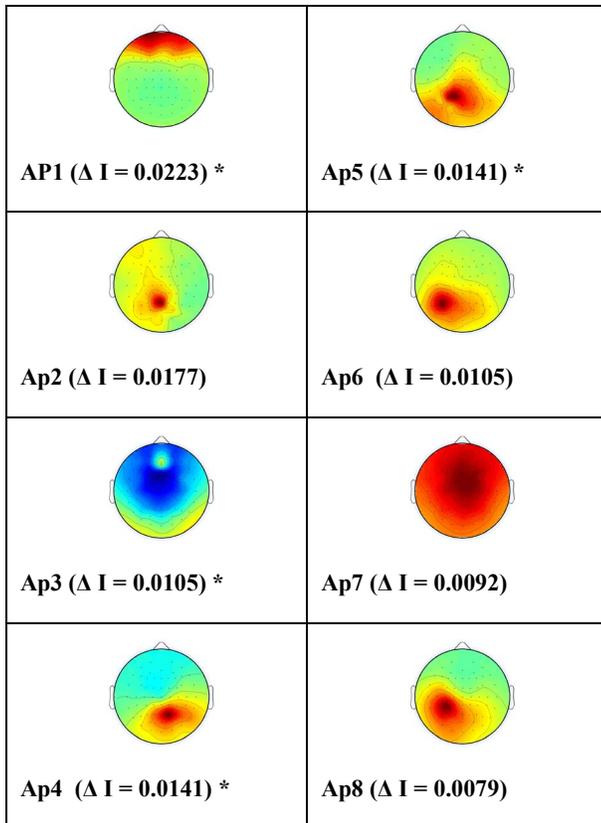

Figure 3 Statistically significant components of the anti-phase task (*). Some other interesting components are also shown. Numerical values depict relative mutual information in bits.

visual brain regions and mutual information values are again increased (two fold on average compared to the Intrinsic condition). This seems completely consistent with the increased task demands of coordinating anti-phase-- essentially doing the opposite of the other. To control this rather difficult interaction situation it is likely that there is a further increase in relevance of each other's actions both in terms of the importance of the visual input and processes related to evaluation and response control in light of it.

These preliminary findings provide an impetus for further investigation in other frequency domains beyond the 10-12 Hz range. Further, it is important to investigate how correct versus incorrect episodes of social interaction as per task instructions may differ in terms of exchange of mutual information. Nevertheless, the present information-theoretic methods appear to be a promising way to quantify brain signals in interactive situations and to understand the mechanisms involved.

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