Dual Logic and Dual Neural Basis for Reciprocal Social Interaction in Eye Contact

Ray F. Lee, *IEEE Member*,

***Abstract*—Dyadic brain interactions during eye contact engage multiple processes and recruit multiple networks. To fully characterize these concurrent activities, it's essential to establish the neural basis for reciprocal social interaction. So far most approaches in this pursuit suffered from the limitations in either insufficient dyadic test instruments or entwined reciprocal and non-reciprocal cerebral responses. To address these two challenges, this study not only employed a dual-head coil to directly acquire dyadic fMRI data, but also developed a dual logic to deductively untwine the reciprocal social interactive state and non-reciprocal affective state in cerebral responses. As results, a data-driven neural basis for visual reciprocal interaction is derived, which mainly consists of imitation-empathy network and mentalizing network to facilitate the exogenous and endogenous dual processes. Applications of the neural basis in extracting dyadic network synchronizations are exemplified. In addition, the dual logic formulated emergence of the endogenous process and predicted the default-mode network.**

I. INTRODUCTION

Scientifically studying dyadic social interaction with fMRI neuroimaging met two main challenges: First was the lack of sufficient instrumentations to directly observe cerebral responses in real-life dyadic social interaction. Second was the lack of any logical procedure to deductively distinguish between the reciprocal social interactive state and the nonreciprocal affective state in their entwined cerebral responses.

The recent development of a dyadic fMRI (dfMRI) system [1] has largely removed the instrumental limitation (the first challenge). It not only provides sufficient spatial and temporal resolution for directly measuring dyadic BOLD hemodynamic activation during face-to-face social interaction, but it also avoids the confounding factors embedded in the indirect methodologies [2] in social interaction studies.

To address the intertwinement issue (the second challenge), a propositional logic model is formularized based on three axioms that transform social stimuli into cerebral responses in cerebral dual systems. Such dual systems resemble the data-driven externally-focused and internally-focused systems framed in social cognitive neuroscience [3], and are defined as exogenous and endogenous systems here. Under this framework, the non-reciprocal affective states can be deductively removed by logical manipulations, and only the reciprocal social states remain in both the exogenous and endogenous dual system.

With both the instrumentation and intertwinement challenges largely resolved, a neural basis for reciprocal social interaction via eye contact has been derived by combining dfMRI experiments and statistical methods that can carry out the logic operations for non-reciprocal state suppression. Applying the neural basis to eye contact analysis reveals multiple parallel synchronization processes in dyadic large-scale brain networks.

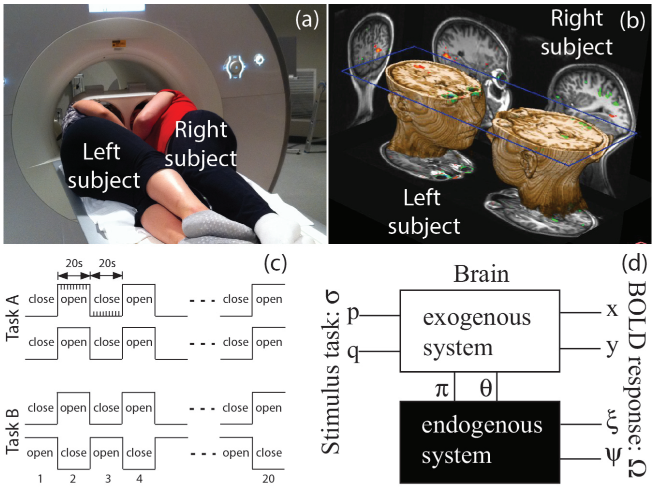

Figure 1

II. THEORY AND METHODS

In the dfMRI experiment, two subjects are laid on their sides facing each other as in Fig. 1a. The relative positions of their eyes and faces are locked as shown in Fig. 1b. Two functional trials with different tasks are performed as illustrated in Fig. 1c in which the two subjects are verbally instructed to open and close their eyes either simultaneously in task A, or alternately in task B. The stimulus-response relation of a brain in this experiment can be modeled by exogenous-endogenous dual system in Fig. 1d.

A. Dual Logic

When the subjects look at their partners in the experiments in Fig. 1b, the exteroceptive stimulus can be decomposed into two dichotomous states, p and q, as defined in Tab. 1. Their logical values are binary "1" or "0" corresponding to observers' eye open or closed. The exteroceptive stimulus of seeing a face can be expressed by a bi-state matrix σ whose functionality is the disjunction of first and second row of the matrix,

$$\sigma = \begin{pmatrix} p \\ q \end{pmatrix}, \; f(\sigma) = p \vee q. \qquad (1)$$

R. F. Lee is with the Princeton University, Princeton, NJ 08544, USA (corresponding author phone: 609-258-4821; email: raylee@princeton.edu)

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

In the exogenous-endogenous dual system model in Fig. 1d, the p and q represent the reciprocal and non-reciprocal stimulus in viewing another's face; their corresponding interoceptive dual pair π and θ represent "mentalizing eyes only" and "mentalizing face without eyes" respectively. The logic values of π and θ are binary "i" or "0", corresponding to observer's eyes being open or closed. Here "i" is the imaginary unit of the complex number.

Table 1 The dual logic

	Exogenous system	Endogenous system
Stimulus σ	p = "I see eyes, direct or averted gaze" q = "I see face without eyes"	π = "I mentalize eyes" θ = "I mentalize face without eyes"
Response Ω	x = "exogenous reciprocal social response" y = "exogenous non-reciprocal affective response"	ξ = "endogenous reciprocal social response" ψ = "endogenous non-reciprocal affective response"
Axioms	$p \leftrightarrow x \vee y$ $q \leftrightarrow y$	$\pi \oplus \xi \wedge \psi$ $\theta \oplus \psi$
$\sigma \vdash \Omega$	task A: $p \vee q \ \vdash \ x \vee y$ task B: $q \ \vdash \ y$ A−B: $(p \vee q) \wedge \neg q \ \vdash \ x \wedge \neg y$ B−A: $q \wedge \neg (p \vee q) \ \vdash \ 0$	B−A: $\pi \wedge \theta \ \vdash \ \neg (\xi \wedge \psi) \wedge \neg \psi$

To establish the logical connection between the stimulus states (p, q; π, θ) and the response states (x, y; ξ, ψ), three axioms are postulated based on the self-evidences and the duality principle in Boolean logic:

Axiom 1: The exteroceptive stimulus p, with either direct or averted gazing, is logically related to the disjunction of the exogenous reciprocal social response (x) and the non-reciprocal affective response (y) by the logical connective of "material equivalence",

$$p \leftrightarrow x \vee y. \qquad (2)$$

Axiom 2: The exteroceptive stimulus q is logically related to the exogenous non-reciprocal affective response (y) in "material equivalence",

$$q \leftrightarrow y. \qquad (3)$$

Axiom 3: The exogenous states (p, q; x, y) and endogenous states (π, θ; ξ, ψ) are dual pairs, and they obey the duality principle in Boolean logic. Since the dual pairs for $\leftrightarrow$ and $\vee$ are $\oplus$ (exclusive disjunction) and $\wedge$ (conjunction) respectively, the relations between the interoceptive stimuli and their responses in endogenous system become,

$$\begin{aligned} &\pi \oplus \xi \wedge \psi, \\ &\theta \oplus \psi. \end{aligned} \qquad (4)$$

Based on these three axioms, all stimulus-response transformations ($\sigma \vdash \Omega$) in this study can be logically deduced, as shown in Tab. 1. In the dual logic terms, the reciprocal social interaction is specified as the exogenous-endogenous reciprocal social states (x, ξ) in cerebral response. Noted that, in task A, exogenous reciprocal social (x) and nonreciprocal affective (y) states are entwined in the cerebral response, as shown in Ω_A in Tab. 2.

Based on rigorous logic deduction, the differentials between task A and B can yield not only suppression of the non-reciprocal state but also the emergence of the endogenous system. To prepare such logical operations, the stimulus tasks (σ) performed by left (L) and right (R) subjects in both the task A and B (in Fig. 1c) are formulated by the bi-state matrices defined in Eq. (1):

$$\sigma_A(L)=\begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix}, \sigma_A(R)=\begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix};$$

$$\sigma_B(L)=\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \sigma_B(R)=\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}. \qquad (5)$$

Here the rows represent the task state p and q; the columns represent the temporal stages of task states in a design block; and the logic values "1" and "0" describe the eyes open and closed.

Table 2 Truth table for cerebral responses in experiment A, B, A-B, and B-A

	State		Ω_A	Ω_B	Ω_+	Ω_-
Exogenous system	x	y	$x \vee y$	y	$x \wedge \neg y$	$y \wedge \neg ((x \vee y) \vee y) = 0$
	0	0	0	0	0	0
	0	1	1	1	0	0
	1	0	1	N/A	1	0
	1	1	1	N/A	0	0
Endogenous system	ξ	ψ				$\neg (\xi \wedge \psi) \wedge \neg \psi$
	0	0				i
	0	i				*0*
	i	0				i
	i	i				0

In the task-space, differential operations between the task matrices $\sigma_A(L)$ and $\sigma_B(L)$ in Eq. (5) generate two composite tasks:

$$\sigma_+ = \sigma_A(L) - \sigma_B(L) = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix},$$

$$\sigma_- = \sigma_B(L) - \sigma_A(L) = \begin{pmatrix} 0 & -1 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & i \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 & 0 \\ 0 & i \end{pmatrix}. \quad (6)$$

In both composite task matrices σ_+ and σ_-, the non-reciprocal stimulus q is removed. Based on Eq. (1), the functionality of task σ_+ becomes $f(\sigma_+)=p$. The fact that the truth-value in σ_+ remains either "0" or "1" suggests that σ_+ is still an exteroceptive task that stimulates the exogenous system. In task σ_-, "-1" is an illegal truth-value, which indicates that it is no longer an exteroceptive task. However, it is equivalent to the product of two legal imaginary matrices due to "$-1=i*i$". The σ_- clearly becomes an interoceptive task matrix whose first and second rows are stimulus π and θ, "mentalizing eyes" and "mentalizing face without eyes". Because the first and second imaginary matrix describe $\pi=(0\ i)$ and $\theta=(0\ i)$ respectively, the functionality of task σ_- then becomes $f(\sigma_-)=\pi\wedge\theta$. Hitherto, the operations in Eq. (6) convert the exteroceptive tasks σ_A and σ_B into one exteroceptive task σ_+ and one interoceptive task σ_-.

The exteroceptive task σ_+ activates exogenous cerebral responses Ω_+; the interoceptive task σ_- activates endogenous cerebral responses Ω_-. Note that the rise of the interoceptive task σ_- from Eq. (6) in task-space causes the emergence of the endogenous response Ω_- in the response-space. From the truth-table in Tab. 2, the exogenous system activation ($\Omega_+=1$) is the result of only a reciprocal social state ($x=1$, $y=0$), while the non-reciprocal affective y-state is suppressed. However, the endogenous system activation ($\Omega_-=1$) is a superposition of both the reciprocal social state ($\xi=1$, $\psi=0$) and the default-mode state ($\xi=0$, $\psi=0$), albeit the non-reciprocal ψ-state suppression.

B. *Data Acquisition and Processing*

All participants gave informed and written consent, which was approved by Princeton University IRB. A total 19 pairs (38 individuals) of subjects were enrolled in the dfMRI experiment. The data acquisition protocols are described in Ref. [1]. The data processing was divided into three modules: preprocessing, GLM regression, and ICA. All three modules were performed mostly by the software package FSL (Oxford University, UK).

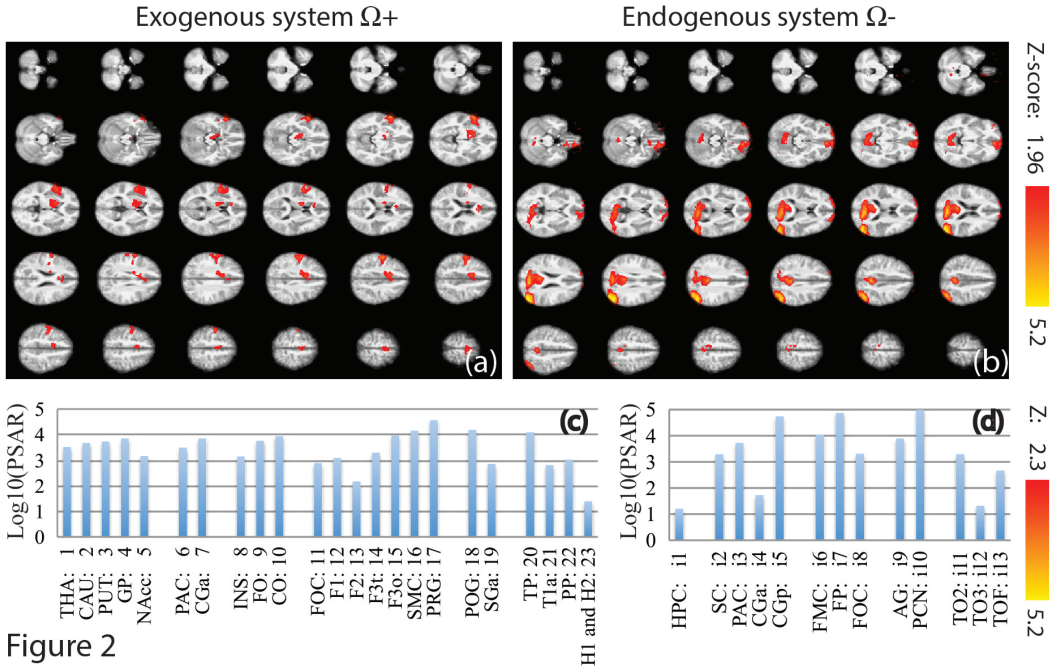

Figure 2

III. RESULTS AND DISCUSSIONS

The dual logic analysis prescribes the operational steps for the y-ψ states suppression and the emergence of the endogenous Ω_- response. Their corresponding experimental steps are described in Fig. 1c; their corresponding computational steps can be implemented statistically with the paired t-test comparison in a group analysis.

A. *Neural basis for reciprocal interaction via eye contact*

The neural basis for visual social interaction was calculated by a paired t-test comparison between Ω_A and Ω_B in a group analysis. The exogenous system Ω_+ and endogenous system Ω_- are shown in Fig. 2a and 2b. Although the t-test threshold for generating Ω_+ and Ω_- is lowered to $Z>1.96$ and p-value<0.05 for scoping finer differences, the inference threshold remains $Z>2.3$ and p-value<0.05 in clustering and labeling Ω_+ and Ω_- to identify the dual system. The probabilistic atlas label distributions for Ω_+ and Ω_- in the MNI152 coordinate are listed in Fig. 2c and 2d respectively. Note that the statistically derived Ω_+ and Ω_- are valid for both left-side and right-side subjects.

For the exogenous system, Ω_+ not only confirms lateral frontoparietal activation [3], but it also identifies the mirror neuron (IFGo, SG) and social empathy network (INS, CGa, imitation circuitry) [4], as well as some afferent and efferent subcortex and motor cortices. For the endogenous system, Ω_- not only confirms the medial frontoparietal activation (FMC and CGp/PCN) [3], but it also adds the left AG, FOC, and posterior HPC to the mix. Such an activation pattern resembles the DMN, except its left hemisphere dominant lateral asymmetry. Given the DMN is usually laterally symmetric, this deactivation on the right hemisphere may offer evidence for the superposition of the reciprocal social state (ξ) and the default-mode state, which is predicted in Tab. 2. Overall, the data-driven dual system Ω_+ and Ω_- support the logical deduction in Tab. 2; and the logical deductions elucidate the experimental results Ω_+ and Ω_-.

B. *Exemplification for an application of the neural basis*

Comprised with the reciprocal x-ξ states for eye contact, the neural basis Ω_+ and Ω_- (Fig. 2) play essential roles in analyzing general visual interactions. One of its applications is to serve as spatial masks for filtering out non-reciprocal affect and to distinguish the dual systems for an arbitrary response in eye contact. For example, the dyadic functional data sets from task A contain multiple parallel processes on multiple brain networks. Many such processes can be extracted by Independent Component Analysis (ICA). However, in the independent components (IC), the reciprocal and non-reciprocal states, as well as the exogenous and endogenous system, are likely entwined. By applying Ω_+ and Ω_- masks to these ICs, the parallel processes only related to reciprocal x-ξ states and their corresponding dual systems could be estimated in a data-driven manner. Furthermore, the labels for Ω_+ and Ω_- in Fig. 2 can serve as a cerebral coordinate for reciprocal interaction (CCRI), as shown in Fig. 3b. Each filtered IC can be projected onto the cerebral coordinate to quantify its dyadic reciprocal interaction.

To analyze the parallel processes in brain-to-brain coupling during eye contact, the probabilistic ICA analysis was applied on the dyadic (not split) data sets from experiment A. With the mixture-modeling threshold set to 0.8, the group level ICA for all 19 paired data sets yielded a total of 35 ICs. Ten of all ICs are dyadic and have temporal courses that correspond to the regressor in Fig. 1c, and have resonance peaks at 0.025Hz in their frequency response, as in Fig. 3c and 3d, which indicate that these ICs are eye-contact related. Multiplying the reciprocal neural basis (Ω_+ and Ω_-) masks to these ICs will filter out the non-reciprocal affective states and distinguish the exogenous and endogenous systems for these ten independent processes during eye contact. Here, only one of the interactive ICs is exemplified for application of the neural basis.

IC #29 was chosen to exemplify filtering and decomposition with the neural basis. Fig. 3a is the original IC #29. After both the left and the right subject activation maps are masked by Ω_+ and Ω_-, the left-subjects labels are distributed on both endogenous (FMC/FP) and exogenous (PRG/POG) in the CCRI; the right-subjects labels are distributed on both exogenous (CGa/PAC, SMC/F1) and endogenous (CGp/PCN/PAC, FMC/FP) in the CCRI, as shown in Fig. 3b. It describes a process in which dyadic endogenous coupling between the left-subjects' (FMC/FP) and the right-subjects' (CGp/PCN/PAC, FMC/FP) seems to be mediated by their exogenous coupling between left-subjects' (PRG/POG) and right-subjects' (CGa/PAC, SMC/F1). The temporal course of this process and its prominent 0.025Hz peak in its frequency response in Fig. 3c and 3d indicate that this brain-to-brain synchronization occurs when dyads' eyes are opened.

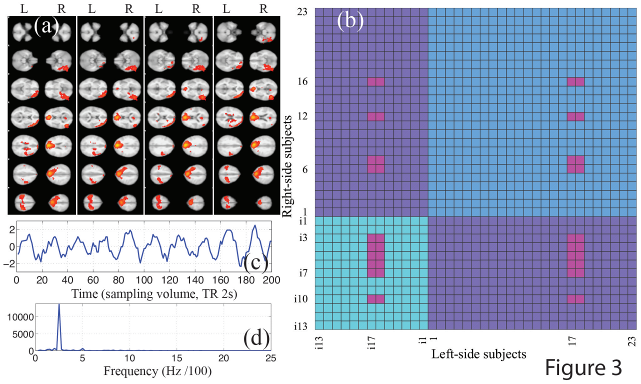

Figure 3

IV. CONCLUSIONS

Overall, the neural basis Ω_+ and Ω_- represent the reciprocal social state (x, ξ), as well as the default-mode state, in exogenous-endogenous dual systems during eye contact. One of the fundamental conclusions of this study is that the exogenous Ω_+ is mainly made of the imitation-empathy system, which reacts to exteroceptive stimuli in "material equivalence" (↔) logic; whereas the endogenous Ω_- is mainly made of the mentalizing system, which reflects on interoceptive stimuli in "exclusive disjunction" (⊕) logic. The dual systems not only have distinct network systems and carry out different functionalities, but also follow a different form of logic.

REFERENCES

[1] R. F. Lee, W. Dai, and J. Jones, "Decoupled circular-polarized dual-head volume coil pair for studying two interacting human brains with dyadic fMRI," *Magn Reson Med,* vol. 68, pp. 1087-96, Oct 2012.

[2] P. R. Montague, G. S. Berns, J. D. Cohen, S. M. McClure, G. Pagnoni, M. Dhamala, *et al.*, "Hyperscanning: Simultaneous fMRI during linked social interactions," *Neuroimage,* vol. 16, pp. 1159-1164, Aug 2002.

[3] M. D. Lieberman, "Social cognitive neuroscience: a review of core processes," *Annual Review of Psychology,* vol. 58, pp. 259-89, 2007.

[4] L. Carr, M. Iacoboni, M. C. Dubeau, J. C. Mazziotta, and G. L. Lenzi, "Neural mechanisms of empathy in humans: a relay from neural systems for imitation to limbic areas," *Proc Natl Acad Sci U S A,* vol. 100, pp. 5497-502, Apr 29 2003.