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Information-theoretic characterization of the neural mechanisms of active multisensory decision making

Ioannis Delis, Robin A. A. Ince, Paul Sajda and Qi Wang

Abstract— The signals delivered by different sensory modalities provide us with complementary information about the environment. A key component of interacting with the world is how to direct ones' sensors so as to extract task-relevant information in order to optimize subsequent perceptual decisions. This process is often referred to as active sensing. Importantly, the processing of multisensory information acquired actively from multiple sensory modalities requires the interaction of multiple brain areas over time. Here we investigated the neural underpinnings of active visual-haptic integration during performance of a two-alternative forced choice (2AFC) reaction time (RT) task. We asked human subjects to discriminate the amplitude of two texture stimuli a) using only visual (V) information, b) using only haptic (H) information and c) combining the two sensory cues (VH), while electroencephalograms (EEG) were recorded. To quantify multivariate interactions between EEG signals and active sensory experience in the three sensory conditions, we employed a novel information-theoretic methodology. This approach provides a principled way to quantify the contribution of each one of the sensory modalities to the perception of the stimulus and assess whether the respective neural representations may interact to form a percept of the stimulus and ultimately drive perceptual decisions. Application of this method to our data identified a) an EEG component (comprising frontal and occipital electrodes) carrying behavioral information that is common to the two sensory inputs and b) another EEG component (mainly motor) reflecting a synergistic representational interaction between the two sensory inputs. We suggest that the proposed approach can be used to elucidate the neural mechanisms underlying cross-modal interactions in active multisensory processing and decision-making.

I. Introduction

Brain functions control human behaviour via the concerted and task-dependent interaction of multiple neural networks over time. The organization and operational principles of such complex systems may be best investigated by using multi-modal approaches, including concurrent measurements of neural activity and behavioural performance. A particular challenge faced in human neuroimaging studies is the study of more natural tasks where a) cross-modal stimulation is generated, i.e. sensory information is provided to multiple senses simultaneously rather than presenting e.g. only visual stimuli alone, and b) the participant is able to perform the task "actively", i.e. they can choose how to explore the stimuli and implement their own strategy for sampling information. Here we propose a novel data analytical methodology that bridges neural activity, sensorimotor behaviour and decision-making performance. The method employs novel information-theoretic measures to probe how the brain a) drives motor behavior to extract relevant information and b) fuses information across sensory modalities to reduce uncertainty in perception of the environment and improve decision-making. We apply our approach to EEG data recorded during an active visual-haptic decision-making task to obtain insights about the neural mechanisms of multisensory integration that drive perceptual decisions during active behaviors.

II. Material and Methods

A. Experimental Procedures

Human subjects were instructed to discriminate the amplitude of two texture stimuli a) using only visual (V) information, b) using only haptic (H) information and c) combining the two sensory cues (VH). Subjects performed the task using a haptic device, called a Pantograph (Fig. 1A) [1,2], which can be programmed to generate tactile sensations that resemble exploring real surfaces. For this binary discrimination task, the workspace of the Pantograph (of dimensions 110mm x 60mm) was split into two subspaces (left - L and right - R, 55mm x 60 mm each) and subjects experienced virtual gratings of different amplitudes (but same wavelength of 10mm) in the two subspaces (Fig. 1B). Subjects placed their right index finger on the plate of the Pantograph and moved it freely in the Pantograph workspace to explore the textures of both subspaces (Fig. 1C) before reporting which one has higher amplitude by pressing one of two buttons on a keyboard (left arrow for L, right arrow for R). In the V condition, visual stimuli that matched the tactile stimuli were presented on a screen of the same dimensions. Amplitudes of the sinusoidal virtual texture in the H condition were mapped onto contrast levels of sinusoidal gratings in the V condition. Importantly, only the part of the workspace corresponding to the subject's finger location was revealed on the screen. In the VH condition, both the visual and the haptic textures were congruently presented. During performance of

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I. Delis is with the School of Biomedical Sciences of the University of Leeds, UK (e-mail: i.delis@leeds.ac.uk).

R.A.A. Ince is with the Institute of Neuroscience and Psychology at the University of Glasgow, UK.

P. Sajda is with the Biomedical Engineering Department and the Data Science Institute of Columbia University, New York, USA.

Q. Wang is with the Biomedical Engineering Department of Columbia University, New York, USA.

the task, electroencephalograms (EEG) active sensing behavior (movement kinematics) and task performance (accuracy-RT) of 7 subjects were recorded.

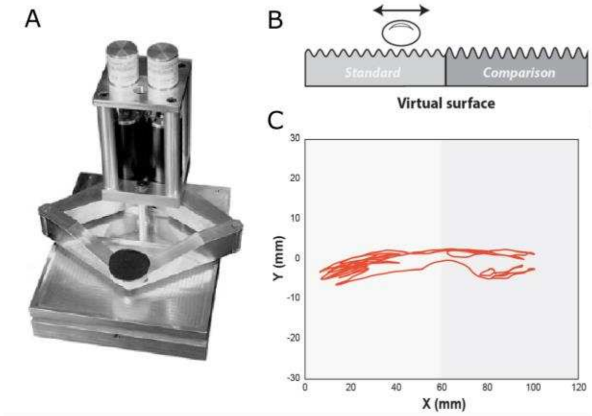

Fig. 1. Experimental design. A. The Pantograph is a haptic device used to render virtual surfaces that can be actively sensed. B. We programmed it to generate a virtual grating texture. The workspace was split into two subspaces that differed in the amplitude of the virtual surface. C. finger trajectory indicating the scanning pattern in one trial.

B. Data Analysis

We then aimed to characterize prominent entrained components of active sensing in the brain. To this end, we used information-theoretic measures (GCMI) [3] to correlate the recorded EEG signals with the behavioral kinematics and extract components of neural activity coupled with components of sensorimotor behavior. A particular advantage of the GCMI effect size is that it is additive; the information (MI) conveyed by independent channels sums linearly. This additivity allows us to easily quantify representational interactions between the two modalities.

Here, we hypothesize that changes in the speed with which subjects explore the visual, tactile or multisensory stimulus are indicative of the strategy they employ for acquiring and accumulating perceptual information and thus reflect active sensing behavior. Hence, we computed the mutual information (MI) between each EEG channel and the active sensing finger velocity varying the lag between the EEG and the velocity in a [-1s,1s] window. We thus obtained a spatiotemporal characterization of the EEG-velocity MIs for all EEG channels and time lags for each experimental condition. Then, we computed the differences between the multisensory MI $I(VH;K)$ and the sum of the two unisensory MIs $I(V:K) + I(H;K)$, termed as interaction information:

$$I_{int} = I(VH;K) - I(V:K) - I(H;K) \quad (1)$$

I_{int} can, if negative, reveal that the two modalities provide less information when observed simultaneously than they do when observed independently, indicating that they share some information. This is termed redundancy, and indicates the EEG reflects a modality invariant representation. If the linear interaction contrast is positive, a better prediction of the EEG response can be made when H and V stimuli are presented together. This is termed synergy, and represents a super-additive cross-modal representational interaction.

III. Results

Specifically, we found an EEG component of negative interaction information indicating a redundant (shared) representation of the V and H modalities. This component occurred at a time lag of 60ms between velocity and EEG activity (EEG lagging) and comprised mainly occipital and frontal activations (Fig. 2A). Another EEG component (with a bilateral topography around motor locations – Fig. 2B) carried positive interaction information (a synergistic representation) about velocity at a 260ms lag.

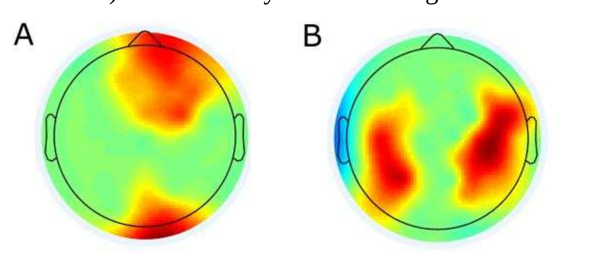

Fig. 2. EEG topographies of negative (A) and positive (B) interaction information between the visual and tactile representations of finger velocity.

IV. Discussion

In this study, we proposed an information-theoretic approach to quantify representational interactions in the brain. We applied it to the joint analysis of neural and sensorimotor behavioral signals recorded during an active multisensory decision-making task in order to characterize when and where in the brain multisensory interactions take place and what is their role in the representation of perceptual information.

We identified an EEG component carrying a common representation of velocity in the visual and tactile modalities. We suggest that this component may represent a supramodal coding mechanism of active sensing behavior. Our analysis also revealed an EEG component carrying an enhanced representation of multisensory processing that is over and above the single-modality representations. This indicates an information gain when multiple sensory stimuli are available, thus this component may represent a neural mechanism of multi-sensory integration during active sensing.

Future work will aim to a) characterize the functional role of these components in decision-making behavior and b) employ simultaneous EEG/fMRI recordings to obtain a full spatiotemporal characterization of the neural components.

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