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Electrophysiological correlates of integrating choice and response time during sequential decision making

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ABSTRACT

Response times (RTs) can provide valuable information about a person's underlying decision processes. To investigate electrophysiological correlates of integrating choice and RTs, ERPs elicited by belief updating in long response times condition (Long-RTs) were compared with those in short response times condition (Short-RTs). In both kinds of conditions, three fictitious persons were arranged in random order (*P1*, *P2*, *P3*) and predicted uncertain state of world. *P3* took a long time in Long-RTs condition. In Short-RTs condition *P3* rapidly made decisions. Participants' task was to infer *P3*'s private signal after observing three fictitious persons' same choice and *P3*'s RTs. ERP results revealed that frontal P200 and N200 distinguished between the two conditions. P200 showed a higher amplitude in Short-RTs condition and might represent early stage valuations of task-relevant perceptual information. N200 showed a more negative amplitude in Long-RTs condition and might reflect conflict between participants' prior knowledge about *P3*'s private signal and *P3*'s long RTs. Our study demonstrates that RTs is an indicator of choice and identifies the temporal process of integrating choice and response time during sequential decision making.

1. Introduction

Economics is built around the idea that a person's preferences or beliefs can only be inferred from his or her choices. However, in many settings, we observe not only the discrete choices, but also the response times (RTs) before a choice is made. RTs is a simple, cheap and attractive indicator of a choice [1]. For example, Konovalov and Krajbich [2] documented that there is a consistent relationship between RTs and strength of risk, time and social preference; and this relationship can be used to infer preferences even when the choices are uninformative or unavailable. Using an information cascade experiment, Frydman and Krajbich [3] showed that RTs contain information that is not contained in choices alone and subjects are able to infer others' private beliefs from RTs without any training.

Behavioral studies have revealed that RTs contain a person's private information (preferences or beliefs) and can provide valuable information about a person's underlying decision processes (a literature review about RTs see Spiliopoulos and Ortmann [4]). However, how the choice and RTs are integrated in the brain during sequential decision making is still unclear.

From a cognitive perspective, integrating choices and RTs information to infer other's preference or belief is a process of belief updating. Recent neuroimaging studies provide evidence for the involvement of medial prefrontal cortex (mPFC) and inferior frontal gyrus (IFG) in belief updating [5–7]. Specifically, the mPFC plays a key role in integrating prior (past experience) and likelihood information (current sensory information), reflecting changes in the behaviorally estimated weights assigned to the two sources of information [5]. d'Acremont et al. [6] found that mPFC encoded likelihood information, whereby IFG encoded the integration of prior and likelihood information. Huber et al. [7] examined neural activity while participant updated private as compared with public information during sequential decision making and found the percentage of choosing with private information was correlated with IFG.

Although fMRI studies localize regions of neural circuitry associated with belief updating and propose the key role of mPFC and IFG in integrating information across time, little is known of the neural activity of how the integration of choices and RTs takes place in the brain. In this paper, we adapted the information cascading experiment developed by Anderson and Holt [9] to explore the electrophysiological correlates of integrating choices and RTs information during sequential decision making. Given the limited research, the hypotheses on

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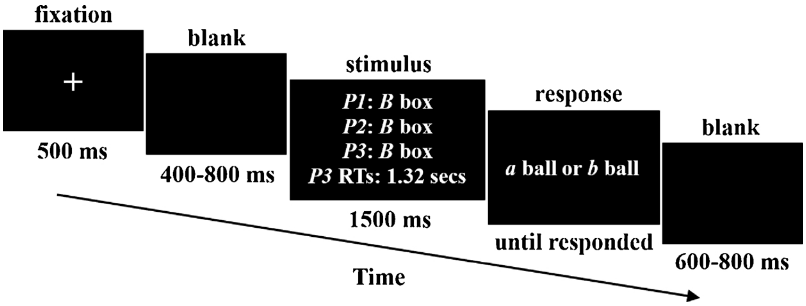

Fig. 1. Time course of a single trial. Each trial began with a 500 ms fixation point and was followed by the blank screen, randomized between 400 and 800 ms. A screen displaying the stimulus presentation was shown for 1500 ms; and a response screen then was appeared until the participants responded. The inter-trial interval was randomized to between 600 and 800 ms.

integrating choices and RTs information during sequential decision making are exploratory.

2. Method

2.1. Participants

A total of 30 healthy students from Nankai University participated in this study for monetary compensation, 2 subjects were excluded due to technical problems and severe artifacts in the electroencephalogram (EEG) data. Therefore, brain activity was fully investigated in 28 participants (10 women, 18 men; mean age = 24.1 years; range = 21–27 years). All participants were right-handed and native Chinese speakers. They had normal or corrected-to-normal vision and had no history of psychiatric or neurological disorders. Informed written consent was obtained before the experiment. The study protocol was approved by local ethics committee of Nankai University.

2.2. Stimuli and task

The present task was based on the information cascade experiment designed by Anderson and Holt [9]. In the experiment, three fictitious persons were arranged in random order and predicted the uncertain state of the world. The prediction was announced publicly when they were made. The order of the three fictitious persons was indexed by *P1*, *P2*, and *P3*. In each trial, there were two possible states of the world, S ε {*A* box, *B* box} and the prior probability of each state was 0.5. Each person's task was to determine which state of the world was more likely. To do so, on his turn the person received a conditionally independent private ball s ε {*a* ball, *b* ball} such that Pr $(s = a \mid S = A) =$ Pr $(s = b \mid S = B) = 2/3$ after observing the predictions of all previous persons.

Two conditions were realized in order to compare the ERP responses to short response times (Short-RTs), and long response times (Long-RTs) processing. The structure in each of the two conditions was the same and displayed the choices of *P1*, *P2*, and *P3*; and additionally, *P3*'s RTs was also displayed. The choices of the three fictitious persons were *A-A-A* or *B-B-B*. In the Short-RTs condition, a short time elapsed for *P3* to make decisions. In the Long-RTs condition, *P3* took a long time to decide. The task of the participant in our experiment was to infer *P3*'s private signal (*a* or *b* ball) by button press on a two-key response pad. The response options of *a* ball and *b* ball in the two conditions were counterbalanced.

We selected about 150 RTs based on the behavioral study of Frydman and Krajbich [3], who found on trials where subjects' private signal was matched with other's choices, and thus had an easy decision, the average RTs was 1.95 s. In contrast, when a subject's private signal was against with other's choices and ultimately chose to follow the other's choices, the average RTs was nearly twice as long 3.79 s. These RTs were tested in a pilot study with four normal participants (age range 22–25 years). Participants were instructed to look at the three fictitious persons' same choices and *P3*' RTs, and then infer *P3*'s private signal. RTs was included in the subsequent experiments only if they made a unanimous judgement about *P3*'s private signal.

Finally, each condition contained 50 RTs, and a total of 100 RTs could be reached a consensus. The average and median RTs was 1.61 s, ranging from 1.20 s to 2.46 s in the Short-RTs condition. The average RTs was 4.89 s, and median RTs was 4.13 s, ranging from 3.53 s to 8.42 s in the Long-RTs condition. All stimulus in the experimental trials had the same structure with three fictitious persons' choices (50 *A-A-A*, 50 *B-B-B*) and P3' RTs (50 short RTs, 50 long RTs) being altered in an equalized, permutated manner.

In order to prevent anticipation of the next event, control trials were randomized interspersed between the experimental trials. Control trials were presented in 20% of the cases. In these trials, the three fictitious persons' choices were *A-B-A*, *A-B-B*, *B-B-A*, or *B-A-B*; the average RTs was 3.97 s, median RTs was 3.34 s, ranging from 1.20 s to 8.26 s. The control trials were not included in the ERP analyses.

2.3. Procedures

EEG was recorded in a small, sound-attenuated, and electrically-shielded chamber. After the EEG electrodes were attached, participants sat in a comfortable chair approximately 100 cm in front of a 23-inch computer monitor. The time course of a single trial was depicted in Fig. 1. Each trial began with the presentation of a single centrally located white fixation cross for 500 ms. Afterwards, the choices of *P1*, *P2*, *P3* and *P3*'s RTs were presented at the center of the screen. This ERP eliciting event was presented for 1500 ms after the presentation of a blank screen for 400–800 ms. After the ERP event, a response displays with two response options were shown until button press on a two-key response pad was registered. We separated the target event from response acquisition to prevent motor artifacts in the ERP event.

The entire experiment comprised of 100 test trials, 20 control trials and 7 practice trials. It is important to note that for ERP analysis only test trials were used. Trials appeared in three blocks of 40 trials. Each block was separated by a break, the duration of which was determined by the participant. The total of 120 trials was presented in a random order, which led to a performing time of about 15 min. At the end of the experiment, five trials would be randomly chosen and participants who predicted correctly received 10 yuan ($1.5, and $0 otherwise) for each trial. The average payoff was 40 yuan ($6.08). The display of the stimuli and acquisition of behavioral data were controlled via the E-Prime software (Version 2.0, Psychology Software Tools, Inc.).

2.4. Electrophysiological recordings and analysis

The EEG was recorded continuously using a 40-channel NuAmps DC amplifier (Compumedics Neuroscan, Inc., Charlotte, NC, USA) with 32 active Ag/AgCl electrodes placed on standard positions according to International 10–20 System. Impedances of all electrodes were kept below 10 kΩ. The ground electrode was positioned at AFz. The data was referenced by the Common Average Referenced. Electrodes below and above the left eye, as well as located on the outer canthi of each eye measured bipolar vertical and horizontal electrooculogram (EOG) activity. Online, EEG was digitized at a sampling rate of 1000 Hz, a 22-bit