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AMBIGUITY AS EMOTIONS: A NEUROECONOMIC STUDY USING THE FUNCTIONAL NEAR-INFRARED SPECTROSCOPY (fNIRS) *

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ABSTRACT

The perceptive of consequentialists is criticized by the studies of the risk-as-feelings. Feelings are not only the components of expected consequences of the decision but also anticipatory emotions. As Damasio's somatic marker hypothesis explains, feelings convey information to guide rational decision making. However, feelings sometimes diverge from cognitive evaluations causing anomalies in decision making. Our study converts this perspective to a new concept, ambiguity-as-emotions, to develop the neuroeconomics of ambiguity using fNIRS. The fNIRS data fully demonstrates ambiguity perception to be a dynamic and spatial pattern of neural activation in the brain specified by the interrelationship between the ambiguity-as-emotions and the cognitive evaluation of ambiguity. FNIRS is a simpler tool than fMRI, causing the subjects minimal stress even when executing lengthy and complex tasks. In the first study on this topic, we use fNIRS and the randomization test to analyze time series data and thus demonstrate the neural activation of the brain when the subjects encounter the robust and persistent uncertainty of Knightian ambiguity. We find the neural activation result only in the brain's left hemisphere as indicative of difficult coordination of pessimistic emotions with a rational but potential cognition. JEL Code: D87.

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I. INTRODUCTION

Criticizing the perspective of consequentialists, Loewenstein et al. (2001) and Slovic et al. (2004) present an alternative hypothesis, the risk-as-feelings perspective. Feelings are components of expected consequences of a decision. Moreover, feelings are considered to operate in the following two ways as anticipatory emotions in uncertain situations. First, as Damasio's somatic marker hypothesis explains, feelings convey information to guide reasonable decision making. Second, however, feelings sometimes diverge from cognitive evaluations to cause anomalies in decision making. Our study converts the concept of risk-as-feelings explained by Loewenstein et al. (2001) and others to a new concept, ambiguity-as-emotions in order to study the neuroeconomics of ambiguity using the recently developed functional near-infrared spectroscopy (fNIRS). We consider the fNIRS data to fully demonstrate ambiguity perception as a dynamic and spatial pattern of neural activation in the brain specified by the interrelationship between ambiguity-as-emotions and the cognitive evaluation of ambiguity.

FNIRS is a simpler and more convenient tool for examining brain activation than the functional magnetic resonance imaging (fMRI) system, and it gives subjects minimal stress to enable performing lengthy and complex tasks. The benefit of using fNIRS is demonstrated by the valuable work of Strangman et al. (2002) which examines fNIRS data to correspond to BOLD fMRI data, the standard now adopted in neuroeconomic experiments.[1]

This study's purpose is to demonstrate the difference between the neural processes of risk and ambiguity perception in lengthy experiment with repeated tasks. We obtain a new insight into the effect of robust uncertainty called Knightian ambiguity on the brain's neural activation.[2] Knightian ambiguity refers to continuous uncertain situations where agents do not have sufficient knowledge about probabilities in uncertain events because of difficulties in learning and pessimistic expectations, i.e., Knightian ambiguity is such a difficult and complicated uncertainty that our limited capacity of understanding cannot easily reduce the ambiguous situation to a merely risky state with known probability in a limited period. In the ambiguity-as-emotions concept, it is noteworthy that Knightian ambiguity's difficulty is not only judged by cognitive evaluation but also felt by the affective mind as anticipatory emotions.

The implications derived from our study extend the theoretical and experimental horizons of neuroeconomics. Hsu et al. (2005), Huettel et al. (2006) and Bach et al. (2009) are seminal papers on the neural processing of risk and ambiguity using the standard fMRI tool. FMRI is an excellent tool for analyzing the spatial structure of neural activation in the brain, but it has limited applicability in representing the features in a lengthy time process with variable neural activation. FMRI methods cannot sufficiently analyze the neural characteristics of robust and persistent uncertainty in Knightian ambiguity during long tasks. The restriction, however, is removed by using the new fNIRS method instead of the standard fMRI tool.

To analyze the fNIRS data, we encounter a new problem in selecting a suitable statistical method. In lengthy experiments with repeated tasks, the time series properties of the fNIRS data need to be carefully considered. The cognitive as well as emotional conditions of the subjects continue to change during decision making in the long-run process because of the brain's memory

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[1] Strangman et al. (2002) finds a strong correlation between fMRI variables and fNIRS measures with oxyhemoglobin providing the strongest correlation.

[2] The number of subjects may seem small. However when the number of subjects is eight, the randomization test requires, as Wampold-Worsham (1986) and Yamada (1998) explains, 8! (= 40320) repeated calculations of the statistical data to obtain the p-value that determines whether to reject the null hypothesis to claim no difference between the dynamic processing of risk and ambiguity in the brain. The number of subjects and that of statistical calculation are thus sufficiently large for our randomization test to obtain the p-value in the non-parametric method.

function. The long-task fNIRS data are expected to have a strong time-series property attributable to memory. To analyze the fNIRS data with its time-series property, instead of using the standard t-test, we use the randomization test developed by Wampold-Worsham (1986), Marascuilo-Busk (1988) and Yamada (1998). The randomization test can be expected to evaluate the p-value and to determine whether to reject the null hypothesis which theorizes no difference between the dynamic process of risk and that of Knightian ambiguity in the brain while executing the repeated experimental tasks. The aim of our fNIRS study is accomplished by adopting the randomization test as an effective statistical method for analyzing data with a time-series property.

In this study, we scan the frontal cortex of the brain by using a lightweight, small-sized and multi-channel digital sensor with a headband to obtain the event-related fNIRS data via a high-sensitivity optical signal. The signal changes dynamically reflecting how the in vivo hemoglobin is combined with oxygen in the blood vessels with high or low cortical activation. Two reasons justify our adopting the frontal cortex scanning plan. First, the low-stress property of the experimental task must be maintained, because only the low-stress property of experimental plan enables us to execute the repeated lengthy tasks. Second, the neural changes in the frontal cortex can provide valuable and integrated information regarding perception and decision making under risk and ambiguity. The frontal cortex has a grater role than other parts of the brain in coordinating emotions with rational cognition for in depth consideration to select a more adaptive and effective alternative behavior. For example, the Somatic marker hypothesis discussed by Damasio (1994,1999, 2003) and Dunn et al. (2006) supports our justification of scanning the frontal cortex. Their hypothesis strongly suggests that the somatic markers are represented and regulated in the frontal cortex where emotions, feelings and rational cognition are coordinated to provide an effective mechanism for determining the best adaptive and effective behavior.Of course, as Ness-Klaas (1994), Rolls (1999), Loewenstein et al. (2001) and others note, this hypothesis does not always succeed in ruling out the possibility that feelings can diverge from cognitive evaluations. In such cases, we can also understand the discordant perceptive condition by observing the changes of neural activation in the frontal cortex. For these reasons, we investigate the dynamic process of higher or lower frontal cortex activation during risk and ambiguity processing in the brain.

The results of neural activation under Knightian ambiguity obtained in our experiment include statistically significant changes in activation of the left orbitofrontal cortex (OFC) as well as the left dorsolateral prefrontal cortex (dl-PFC), when the subjects perceive increased complexity and difficulty in executing the risky games. The emotional and cognitive dynamic change with feelings of increased difficulty in the risky games can be interpreted as the generation of ambiguity aversion with reduced motivation and pessimistic expectations. The activation of specific areas of the OFC and dl-PFC are consistent with findings by the previously cited seminal neuroeconomic studies, but our neural activation result is only observed in the brain's left hemisphere. Based on the studies by Goel et al. (1997) and Goel-Dolan (2004), we can interpret the neural activation of the left hemisphere of the brain under ambiguity as indicative of difficult coordination of the pessimistic emotions about executing risky games with a rational but potentially required function of induction to actively learn the hidden information under uncertainty.

II. METHODS

The experimental games are played by eight healthy right-handed subjects, four males and four females aged 20-24.[3] The subjects are prohibited from eating within two hours before

[3] The number of subjects may seem small. However when the number of subjects is eight, the randomization test requires, as Wampold-Worsham (1986) and Yamada (1998) explains, 8! (= 40320) repeated calculations of the statistical data to obtain the p-value that determines whether to reject the null hypothesis to claim no difference between the dynamic processing of risk and ambiguity in the brain. The number of subjects and that of statistical calculation are thus sufficiently large for our randomization test to obtain the p-value in the non-parametric method.

executing the games. In order to execute the experimental games, each subject enters a shielded tent in a quiet room protected from electromagnetic interference (EMI) and noises.

We use the convenient and low-stress fNIRS tool to scan primarily the frontal cortex of the brain.[4] As illustratied by Figure I, fNIRS uses lightweight, small-sized and multi-channel digital sensors with a headband in order to obtain the event-related fNIRS data through a high-sensitivity optical signal that changes dynamically reflecting how the in vivo hemoglobin is combined with oxygen in the blood vessels with high or low cortical activation.

(Figure I) FNIRS Multi-channel Digital Sensors with Headband

The location of the 16 channels are illustrated in Figure II provided by NIRS-SPM software for statistical analysis of fNIRS signals. We obtain the event-related high-sensitivity optical signal from these channels. The 8th and 9th channels are placed at the center of each subject's forehead.

(Figure II) Locations of the 16 fNIRS Channels

The experimental game presented to the subjects is the AB type game composed of two kinds of tasks A and B. First, the subjects execute task A repeatedly in the baseline period, then the task changes from A to B for the experimental period. The subjects execute task B repeatedly in the next experimental period. As illustrated by Figure III, the randomization test requires that the subjects are randomly allocated to the games having different task compositions. Specifically before executing the games, each subject is randomly allocated to the i-th game (i = 1,2, ... 8) which is composed of the (4 x i) rounds of task A and the (36 - 4 x i) rounds of task B, where 36 is the total number of task executions. Each task requires 10 seconds to execute, and the total time to complete the experimental game is 6 minutes.

(Figure III) Experimental Design for Randomization Test

As explained in Figure IV, task A's content begins with the first screen of the computer monitor displaying a magician (disguised by an undergraduate at Aoyama-Gakuin University) showing his spade card. After two seconds, the next screen displays a choice for the subject between two alternative cards which are laid face down on a table. One of the cards is a spade and the other a heart, but their suit marks are not visible to the subject. He is neither informed of which is the spade card (the heart card) nor aware of what rule will change the placement of the two cards for every task. In our experiment, we randomly change the placement of the two cards with a prior probability of 50%. If the subject chooses the spade that is identical to the magician's card, he wins $1 per task, but if he chooses the heart card which is different from the magician's card, he loses $1. Playing the task A repeatedly, profit maximization requires the subject to learn what rule will change the placement of the two cards that lie face down on the table.

(Figure IV) Task A in Game AB

Figure V illustrates the content of task B. The difference between task B and task A is only the card opened by the magician on the first screen. While a spade card is shown in task A, an "unknown card" is shown in task B. The subject does not know whether this unknown card is a spade or a heart. He is only informed that the unknown card changes randomly to be a spade or a heart with a prior probability of 50%. The subject wins when he chooses the same suit card from the

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[4] Our fNIRS is the Spectratech OEG-16 model. This model has previously been installed and used for scientific research such as Kita et al (2011).

alternative choice. Task B is repeated during the experimental period, and the subject is required to determine their optimal behavior in choosing one of the alternative cards.

After the games conclude, an interview survey is conducted. The subjects are asked to answer the following two questions. (1) Rank the order of the difficulty of games A and B. (2) Explain your perception about playing these experimental games. What is the strength of your psychological stress while executing the games?

(Figure V) Task B in Game AB

III. RESULTS

The subjects execute task A in the baseline period, then the task changes from A to B for the experimental period. We investigate the effects of the task change on the event-related fNIRS data which reflect how the in vivo hemoglobin is combined with oxygen in the blood vessels with high or low cortical activation. As is already mentioned, the fNIRS data of the changes in oxy-Hg levels are demonstrated by Strangman et al. (2002) to correspond to the changes in the BOLD data of the fMRI, a standard now adopted in neuroeconomic experiments.

Our results are shown in Table I and Figure VI. Table I shows the p-values of all channels obtained by the randomization test. The method for calculating the p-value by the randomization test is provided by Wampold-Worsham (1986) and Yamada (1998). Use of the randomization test is justified because our experimental study is a repeated-task study where the fNIRS data are expected to have strong time series correlation. Table I implies that the change in data at channel 12 is statistically significant at the 5% level, and the change in data at channel 16 is significant at the 10% level.[5]

Figure VI indicates the average values of the event-related fNIRS data at channels 12 and 16 for all the subjects. The data for neural activation at channels 12 and 16 show the same pattern increasing remarkably, when task A changes to task B.

(Table I) The P-values of the Channels
(Figure VI) The Average Values of fNIRS Data at Channels 12 and 16

IV. DISCUSSION

Channels 12 and 16 where we obtained the statistically significant data from fNIRS are respectively placed on the left orbitofrontal cortex (OFC) and the left dorsolateral prefrontal cortex (dl-PFC). The OFC is Brodmann area 11, and dl-PFC is Brodmann areas 9 and 46. The implications of these experimental results are obtained by comparing our results with those of the neuroeconomic studies by Hsu et al. (2005), Huettel et al. (2006) and Bach et al. (2009), also considering the implications of our previous study (Nakagome et al. 2011).

Hsu et al. (2005), Huettel et al. (2006) and Bach et al. (2009) are the seminal papers on investigating the neural processing of risk and ambiguity by fMRI. They present neurological evidence that the human brain perceives risk and ambiguity differently. The neurological responses to ambiguity,particularly the higher activation of the posterior inferior frontal sulcus (pIFS), come from the anticipation that hidden information under ambiguity is searched for to reduce to risk (uncertainty with known probabilities). The neural activation of pIFS mediates the transition mechanism from ambiguity to risk in the learning process of an ambiguous probability distribution.

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5 The event-related fNIRS data of the changes in oxy-Hg levels are measured by establishing the fact that the oxy-Hg level at the starting point of the experiment is fictitiously determined to be zero as a reference point.

There remains an open issue unexamined in neuroeconomics to date. Will the reverse transition occur? What psychological and neurological mechanism may trigger and promote the reverse transition process where the perception of risk reverts to the perception of ambiguity? In our previous study (Nakagome et al. 2011), we used the digital electroencephalography (EEG) to examine the generation of the reverse change in CNV when subjects perceive increased difficulty in risky games, a phenomenon that implies the emergence of a different perception called ambiguity aversion. The present study uses the same experimental tasks A and B as those in the previous study. And the present study's interview survey shows that all subjects perceive the difficulty of the game to increase remarkably, when the task changes from A to B.[6] Thus, we consider that the perception of ambiguity is also generated in the present experiment.

Now we proceed to the next issue. EEG can represent the features in a time process with variable neural activation, but it is limited to analyzing the spatial structure of brain activation. Therefore, in this study, we use the fNIRS system and a randomization test which together can analyze the spatial structure of neural activation with time resolution. As explained in the Results section, our fNIRS study demonstrates that the neural activation in the left orbitofrontal cortex (OFC) and the left dorsolateral prefrontal cortex (dl-PFC) increases remarkably to the level of statistical significance, when the task changes from A to B implying that the perception of risk will revert to the perception of ambiguity with the feeling of increased difficulty in executing the games. It is noteworthy that these activated areas of the brain border the brain areas that previous experimental studies observe to be activated. The dorsolateral prefrontal cortex (dl-PFC) which we observe to be activated borders the posterior inferior frontal sulcus (pIFS). However in our results, we have left a question: why only the left side of the brain areas is activated. We will take our cue from the explanation provided in Goel et al. (1997) and Goel-Dolan (2004).

These studies on cognitive science examine the neural basis for investigating inductive and deductive reasoning by using fMRI with an event-related design. Goel-Dolan (2004) and others find that the left dorsolateral prefrontal cortex (Brodmann areas 8 and 9) shows greater activity during induction than deduction. In addition, Inductive processing is evaluated for plausibility which is a function of our knowledge of the world. Thus, activation of the left dorsolateral prefrontal cortex is interpreted to indicate that it is expected and required to quickly understand the context and the rules of the world.

We consider the implications of ambiguity aversion generation in our study.When the subjects feel the generation of ambiguity, they notice that their mind loses the emotional and cognitive basis to perceive risk with a known probability.In order to begin again from "the lost world," they must learn new information to understand the world. This is a reasonable explanation of left dorsolateral prefrontal cortex activation with cognitive judgement, when the perception of risk reverts to the perception of ambiguity.

One open question remains why is the left OFC also activated? Studies conducted by Bechara et al. (1994), Kringelbach (2005) and Volz et al. (2008) among others demonstrate that the OFC function is usually explained as regulating our planning behavior by coordinating feelings with cognitive evaluations. The OFC is expected to manage and control our mind with psychological reward and punishment in order to decrease pessimistic feelings' negative effects on our behavior. In our study, however, the interview survey after the experiment shows that the subjects strongly perceive difficulty in executing the games with reduced motivation and pessimistic expectations that decrease their attempts to win the games. Therefore in our experiment, the OFC is interpreted as ineffective in coordinating the difficult and pessimistic feelings with the potential and rational requirement for induction to actively learn the rules of the world.
Here we consider that this neuro-behavioral struggle between feelings and cognitive judgements occurs more often between neighboring neural areas than between distant areas. We can resolve the

[6] However, as our previous paper (2011) shows, the feelings of difficulty in executing games does not coincide with the theoretical difficulty in calculating the optimal strategies in the games. This is the perception gap which generates with ambiguity aversion in the experimental games. See our previous paper (2011) for further details.

open question regarding the activation of only the left OFC by explaining that the potentially required neural area for induction exists only in the left dorsolateral prefrontal cortex (dl-PFC) and the left OFC is located nearer to the left dl-PFC than the right OFC. The pattern of activations in neural areas under the robust uncertainty of Knightian ambiguity exhibits the remarkable feature of spatial bias to the left hemisphere which demonstrates that reduced motivation and pessimistic feelings are not completely harmonized with cognitive functions and therefore suppress the potential requirement for actively learning new information.

V.SIGNIFICANCE AND IMPLICATIONS

Hsu et al. (2005), Huettel et al. (2006) and Bach et al. (2009) are the seminal papers on investigating the neural processing of risk and ambiguity by fMRI. FMRI is an excellent tool for analyzing the spatial structure of activation in the brain, but it has only a limited time resolution to display the long-term features of neural activations. Using the recent developed simple and low-stress brain imaging fNIRS, our study extends the experimental horizon of the neuroeconomics to the research field of Knightian ambiguity which is a long-term robust uncertainty. We demonstrate that the changes in activation of the left dorsolateral prefrontal cortex (dl-PFC) as well as the left orbitofrontal cortex (OFC) are statistically significant, when the perception of risk reverts to the perception of ambiguity with the feeling of difficulty in executing the games. The pattern of activations in neural areas under the robust uncertainty of Knightian ambiguity shows the remarkable feature of spatial bias to the left hemisphere which represents reduced motivation and pessimistic feelings as not completely coordinated with cognitive functions to suppress the potential requirement for actively learning new information.

Our study is, however, the first attempt to investigate the neural processing of Knightian Ambiguity in the brain. Further analyses are needed to extend the neural scan to all brain areas to examine the overall effects. It is also interesting to analyze the interrelationship among human agents in a social context with complexity and uncertainty. The behavioral and neuroeconomic analysis must be extended to study the “risk society” described by Ulrich Beck (1986) where the perception of risk and ambiguity amplify one another under the interrelationships between multiple human agents. The simple and convenient fNIRS tool with minimal stress to subjects will open new possibilities for neuroeconomic research.

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TABLE I

The P-value of the Channels

AB	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6	Ch7	Ch8
P-value	0.241	0.12	0.219	0.137	0.211	0.253	0.165	0.382

AB	Ch9	Ch10	Ch11	Ch12	Ch13	Ch14	Ch15	Ch16
P-value	0.196	0.123	0.272	0.05	0.108	0.205	0.311	0.081

These P-values of the 16 channels are provided by the randomization test to analyze the event-related fNIRS data of the changes in oxy-Hg levels that have strong time series correlation. The change in data at channel 12 is statistically significant at the 5% level, and the change in data at channel 16 is significant at the 10% level. Channels 12 and 16 are respectively placed on the left orbitofrontal cortex (OFC) and the left dorsolateral prefrontal cortex (dl-PFC).

FIGURE I

FNIRS Multi-channel Digital Sensors with Headband

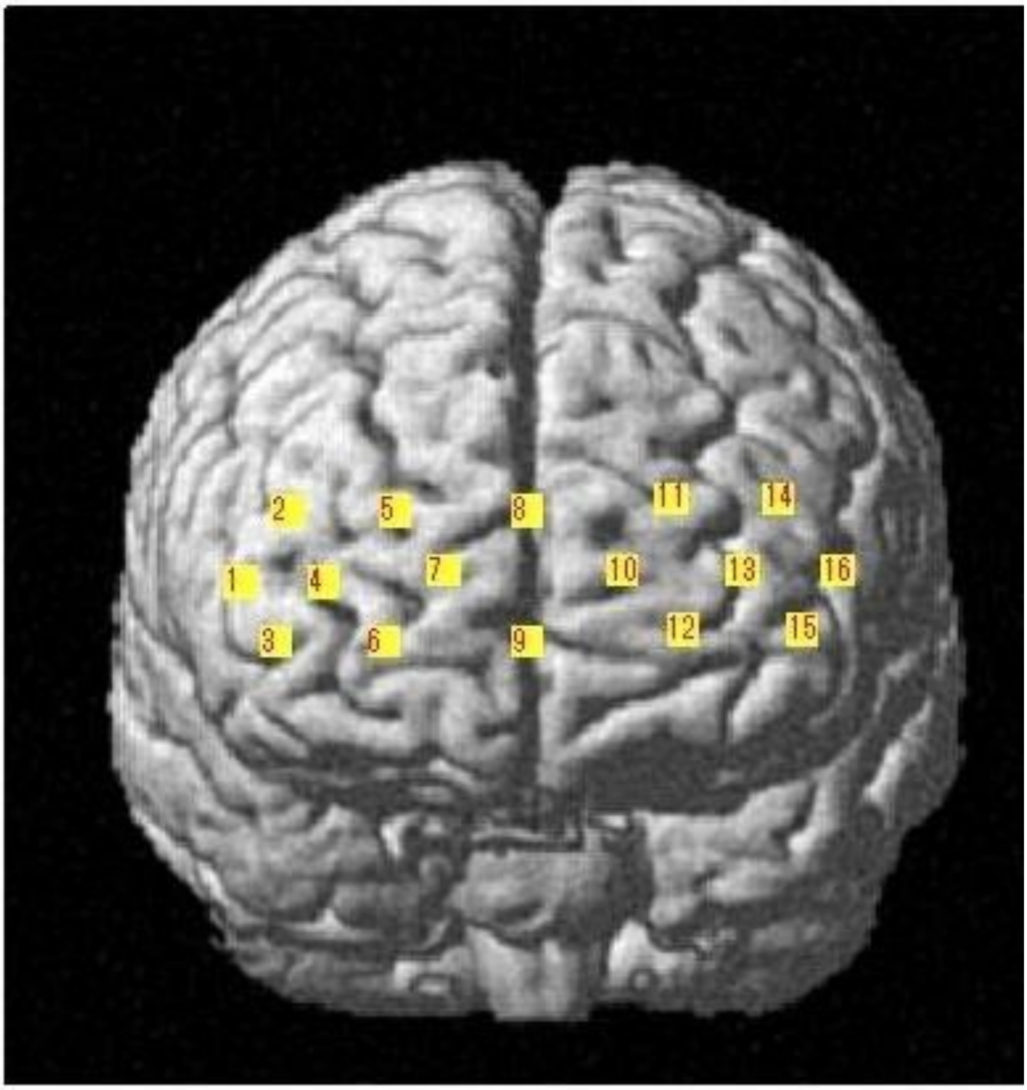


FIGURE II

Locations of the 16 fNIRS Channels

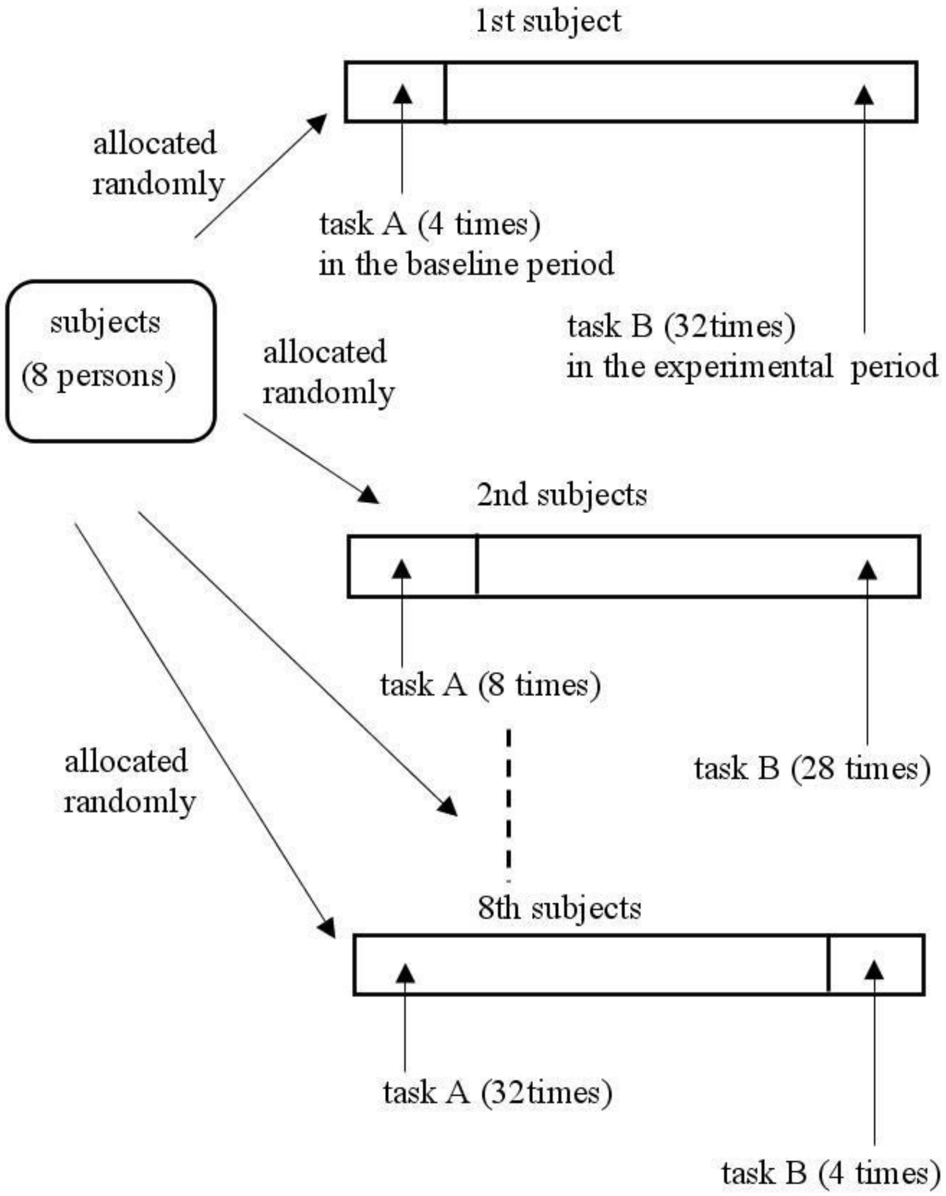


FIGURE III

The Experimental Design for Randomization Test

FIGURE IV

Task A in Game AB

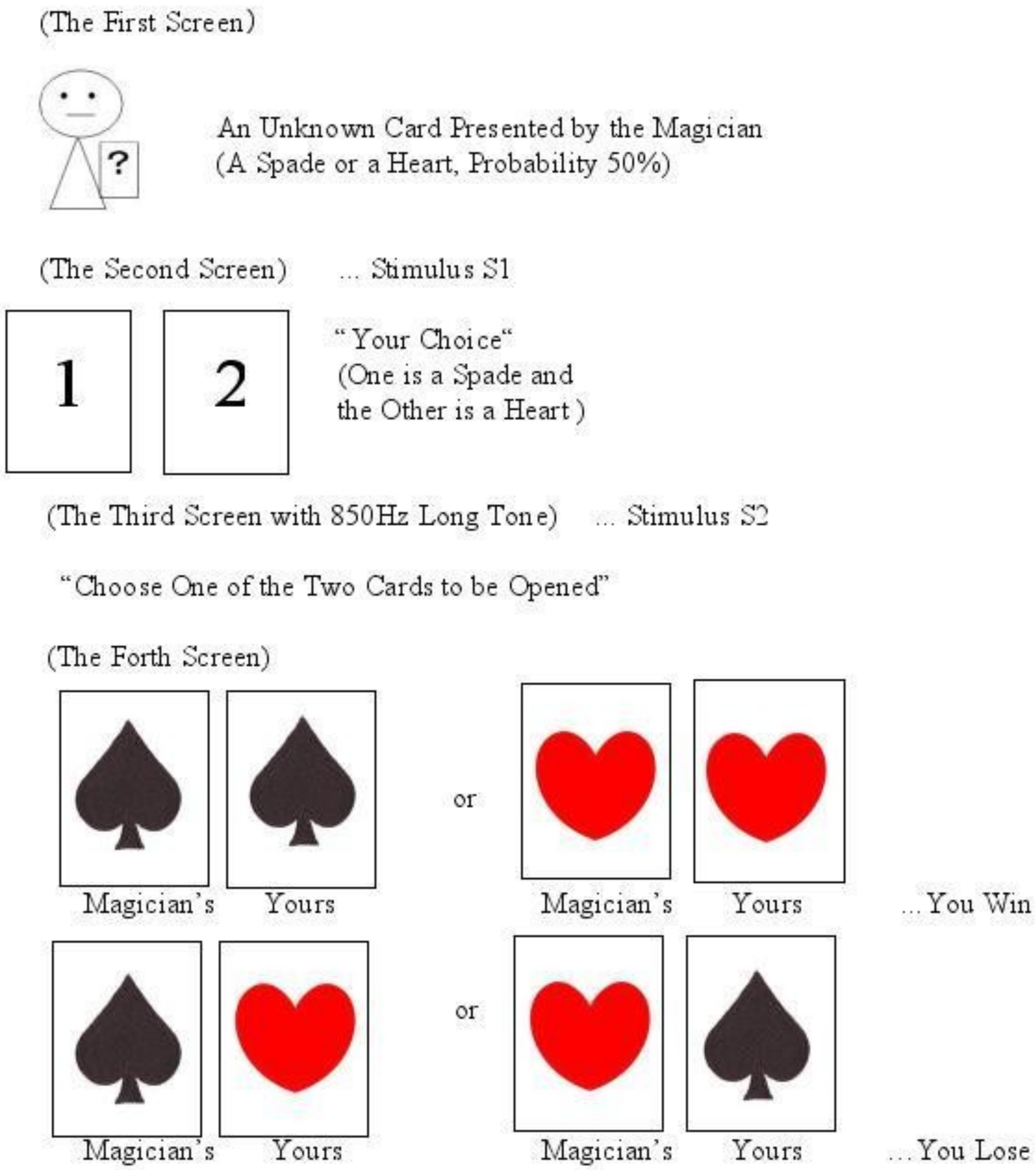
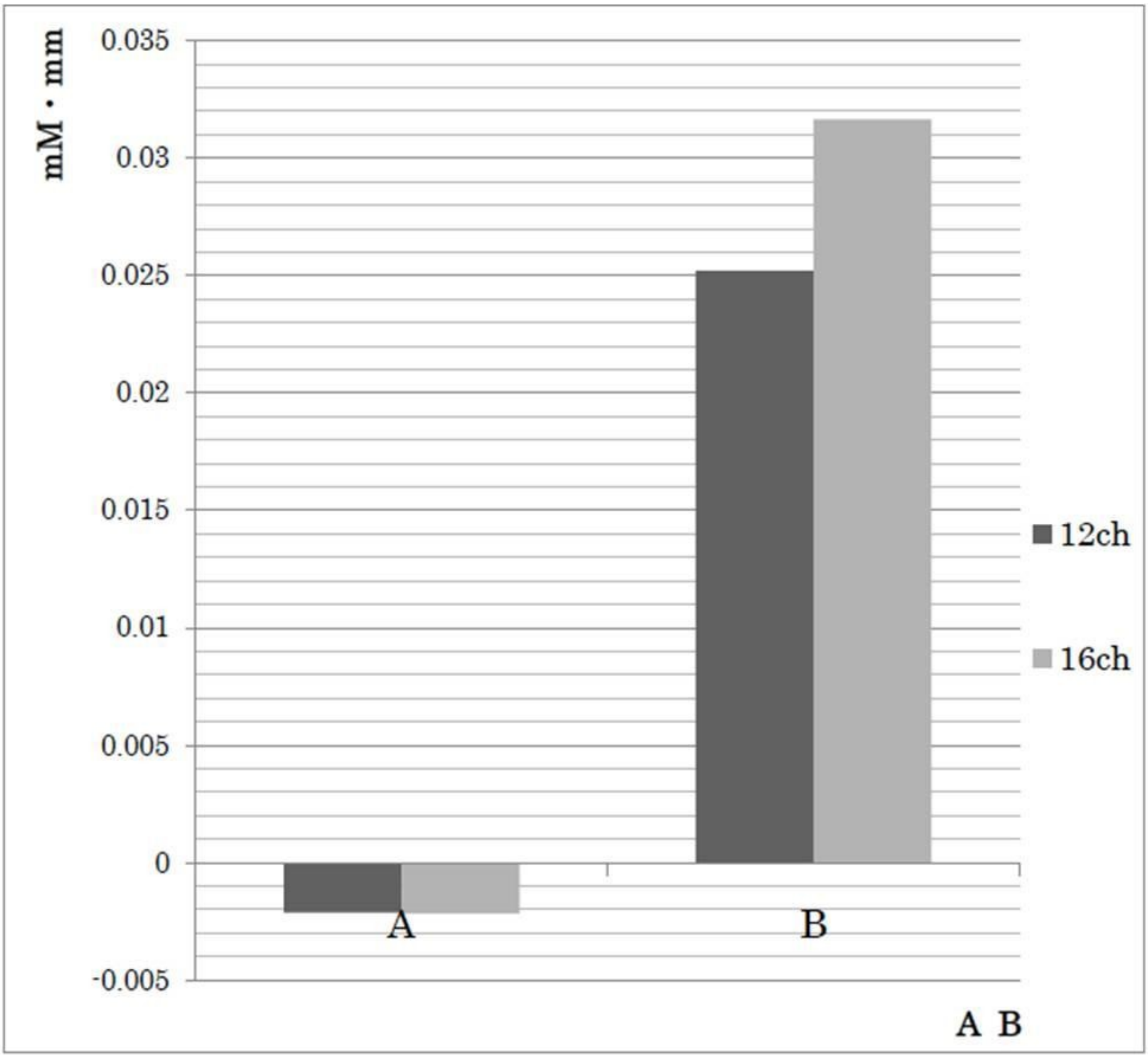


FIGURE V

Task B is Game AB



	A	B
12ch	−0.00212	0.025213
16ch	−0.00215	0.031653

FIGURE VI

The Average Values of fNIRS Data at Channels 12 and 16