International Journal of Neuropsychopharmacology (2020) XX(XX): 1–11

doi:10.1093/ijnp/pyaa044
Advance Access Publication: July 23, 2020
Regular Research Article

REGULAR RESEARCH ARTICLE

Higher Risk Taking and Impaired Probability Judgment in Behavioral Addiction

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Abstract

Background: Accumulating evidence suggests that deficits in decision-making and judgment may be involved in several psychiatric disorders, including addiction. Behavioral addiction is a conceptually new psychiatric condition, raising a debate of what criteria define behavioral addiction, and several impulse control disorders are equivalently considered as types of behavioral addiction. In this preliminary study with a relatively small sample size, we investigated how decision-making and judgment were compromised in behavioral addiction to further characterize this psychiatric condition.
Method: Healthy control subjects (n = 31) and patients with kleptomania and paraphilia as behavioral addictions (n = 16) were recruited. A battery of questionnaires for assessments of cognitive biases and economic decision-making were conducted, as was a psychological test for the assessment of the jumping-to-conclusions bias, using functional near-infrared spectroscopy recordings of prefrontal cortical (PFC) activity.
Results: Although behavioral addicts exhibited stronger cognitive biases than controls in the questionnaire, the difference was primarily due to lower intelligence in the patients. Behavioral addicts also exhibited higher risk taking and worse performance in economic decision-making, indicating compromised probability judgment, along with diminished PFC activity in the right hemisphere.
Conclusion: Our study suggests that behavioral addiction may involve impairments of probability judgment associated with attenuated PFC activity, which consequently leads to higher risk taking in decision-making.

Keywords: behavioral addiction, impulse control disorder, cognitive bias, probability judgment, prefrontal cortex

Introduction

Behavioral addiction has recently come into the limelight—along with the inclusion of gaming disorders and Internet use disorder, which are prototypical behavioral addictions—with its addition into the diagnostic category of addiction in the International Classification of Diseases, 11th Revision (World Health Organization, 2018; Derevensky et al., 2019). Several impulse control disorders, such as kleptomania and paraphilia, are also suggested to meet the criteria of behavioral addiction, such that these psychiatric conditions are often interchangeably considered as behavioral addictions (Robbins and Clark, 2015; Grant and Chamberlain, 2016; Kardefelt-Winther et al., 2017; Petry et al., 2018). Thus, behavioral addiction is thought to be a conceptually new and premature psychiatric condition, with its definition equivocal and changing, due to insufficient studies and insights (Robbins and Clark, 2015; Grant and Chamberlain, 2016; Kardefelt-Winther et al., 2017; Petry et al., 2018).

The dual process model has a long history that can be dated back to the pioneering proposals by Pavlov (2010) and Freud (1933) almost a hundred years ago. The model explains that the human psychological system is roughly divided into 2 processes; 1 is the intuitive process, which is characterized as fast and automatically generated; and the other is the reflective process,

Received: April 10, 2020; **Revised:** June 6, 2020; **Accepted:** June 16, 2020

Significance Statement

Behavioral addiction has recently been gaining extensive attention in society, along with the emergence of new psychiatric conditions of it, such as gaming disorders and Internet use disorder. However, behavioral addiction is still a conceptually new disorder, and its criteria have not yet been determined. To further elucidate what characteristics may be associated with behavioral addiction, we investigated whether cognitive biases, systematic errors in judgment, and decision making were different between healthy subjects and patients diagnosed with kleptomania and paraphilia, which are both psychiatric conditions thought to fit into the criteria of behavioral addiction. Our study demonstrates that although there are no clear differences in the cognitive biases between behavioral addicts and healthy subjects, behavioral addicts exhibit impairments of probability judgment associated with compromised prefrontal cortical activity, which consequently led to higher risk taking in decision-making.

which is characterized as conscious and effortful, and yields inhibitory effects on the intuitive process (Evans, 2008; Kahneman, 2011; De Neys and Pennycook, 2019; Grayot, 2020). These intuitive and reflective processes have been denoted by various nomenclatures in different studies, such as first versus second signals, experiential versus analytical, heuristic versus systematic, and system 1 versus system 2 (Evans, 2008). (Hereafter in this manuscript, we refer these processes as first vs second signals, based on the pioneering proposal by Pavlov in 1927 [Pavlov, 2010]). Given that such a dichotomy of psychological processes could be attributed to prefrontal cortical (PFC) cognitive control over subcortical, limbic-striatal systems that mediate salience and habitual responses, an imbalance of the dual process model toward stronger first (intuitive) and weaker second (reflective) signals is suggested to underlie the mechanisms of addiction (Bechara, 2005; Evans and Coventry, 2005; McClure and Bickel, 2014). Accumulating evidence suggests that dual process deficits with dysfunction of PFC inhibitory control over habitual or prepotent responses are indeed involved in addiction (Baicy and London, 2007; Ivanov et al., 2008; London et al., 2015; London, 2020). In addition, a recent mega-analysis investigating impairments of behavioral inhibition in addicted subjects with several different substances (alcohol, tobacco, cannabis, amphetamine, cocaine, ecstasy) has demonstrated that only lifetime cannabis use is associated with suboptimal inhibition. Moreover, lifetime cannabis use moderates tobacco's effect on response inhibition, and tobacco use is associated with suboptimal inhibition only in cannabis non-users (Liu et al., 2019).

A crucial component of the dual process model is cognitive biases, which are systematic errors or deviations of thoughts in judgments and decision-making (Tversky and Kahneman, 1974, 1981; Kahneman, 2011). Cognitive biases are primarily associated with the first signal (Kahneman, 2011), and present in a range of decision-making and judgment scenarios, such as economic decision-making and probability judgments (Tversky and Kahneman, 1974, 1981; Kahneman, 2011). A number of questionnaires and psychological tests have been developed to examine cognitive biases, such as the cognitive reflection test, which comprises a series of questions designed to prepotent answers generated from the first signal over the second signal (Frederick, 2005; Toplak et al., 2011), and the jumping-to-conclusions test, in which decision biases in probability judgments are examined (Garety et al., 1991; Lincoln et al., 2010; Evans et al., 2012; Evans et al., 2015).

Collectively, since cognitive biases are associated with the first signal and the imbalance toward an enhanced first signal and attenuated second signal is expected to underlie addiction, amplification of cognitive biases may be observed in behavioral addiction. In this study, we investigated cognitive biases in patients with 2 specific types of symptoms fitting into behavioral addiction: kleptomania and paraphilia. To do so, a set of questionnaires and a psychological test were conducted, along with measuring PFC activity using functional near-infrared spectroscopy (fNIRS).

Methods

Subjects

This study was conducted in accordance with the Declaration of Helsinki and the Ethical Guidelines for Medical and Health Research Involving Human Subjects by the Japanese Ministry of Health, Labour, and Welfare. All experimental procedures were approved by the Human Research Ethics Committee of Kyoto University Primate Research Institute and the Ethics Committee of Kyowa Hospital. As controls, a total of 31 healthy adult subjects without smoking and psychiatric histories, who were either working staff members of Kyowa Hospital (n = 25) or undergraduate students in Kyoto University (n = 6), were recruited. For the group with behavioral addiction, hospitalized adult patients who were diagnosed with behavioral addictions (n = 16) of different symptoms— gambling disorders (n = 1), kleptomania (n = 10), and paraphilia (n = 5)—were recruited. Upon enrolling into the study, written informed consent was obtained from all participants in advance of experiments. Patients were diagnosed by the psychiatrist (MW), who has been specializing in addiction treatments for more than 22 years. Patients were diagnosed based on the criteria of both the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (American Psychiatric Association, 2013), and the International Classification of Diseases, 10th Edition (World Health Organization, 1992). A severity level was judged using the Japanese version of the addiction severity index (Senoo et al., 2006). Experiments were conducted with patients at the time of hospitalization during the period between May 2019 and February 2020. Some patients who had a history of other comorbid psychiatric conditions or who could not understand the instructions on the administered tests were excluded for the study.

A short form of the Japanese version of the Wechsler Adult Intelligence Scale–III, consisting of the information test in the verbal comprehension index and the picture completion test in the perceptual organization index, was conducted to create an estimated full-scale intelligence quotient (eFIQ) of participants. Dairoku, Kobayashi, and their colleagues (Kobayashi et al., 1993; Dairoku et al., 2008) have demonstrated that the use of this short form can reliably create an eFIQ with correlation coefficients of reliability and validity at 0.87–0.88 and 0.81–0.83, respectively.

A sample structure with regard to the diagnosis, gender, age, and eFIQ data is summarized in Table 1.

Table 1. Sample Structure With Regard to Diagnosis, Gender, Age, and Estimated Full-Scale Intelligence Quotient

				Age				eFIQ			
	Diagnosis	Gender	n	Min	Max	Mean	s.e.m.	Min	Max	Mean	s.e.m.
BA	PP	male	5	29	58	44.0	5.34	61	115	90.4	11.1
		female	0	-	-	-	-	-	-	-	-
		Σ	5	29	58	44.0	5.34	61	115	90.4	11.1
	KM	male	3	20	24	21.7	1.20	61	97	45.4	5.54
		female	7	25	72	83.0	11.1	64	109	82.0	6.75
		Σ	10	20	72	38.3	6.25	61	109	82.3	5.42
	GD	male	1	-	-	31	-	-	-	70	-
		female	0	-	-	-	-	-	-	-	-
		Σ	1	-	-	31	-	-	-	70	-
	Σ	male	9	20	58	35.1	4.61	61	115	85.7	7.05
		female	7	25	72	45.4	5.54	64	109	82.0	6.75
		Σ	16	20	72	39.6	3.68	61	115	84.2*	4.88
CT		male	13	18	45	32.7	2.79	85	133	103	4.58
		female	18	19	58	38.7	2.71	70	118	99.5	2.65
		Σ	31	18	58	36.2	2.00	70	133	101	2.44

*Statistically significant difference compared to CT ($P < .05$).
Abbreviations: Σ, total; BA, behavioral addicts; CT, control subjects; eFIQ, estimated full-scale intelligence quotient; GD, gambling disorder; KM, kleptomania; PP, paraphilia; s.e.m., standard error of the mean.

Questionnaires

To assess cognitive biases, 2 paper-based questionnaires were administered. First, the extended version of the cognitive reflection test was used, which consisted of the original 3 questions from the study by Frederick (2005) and 2 additional questions from the study by Toplak and colleagues (2011), totaling 5 questions. These questions are designed to assess an ability to suppress incorrect answers with cognitive biases generated from the first signal, and to reach correct answers generated from the second signal. The type of answers can be allocated into either a correct answer, biased incorrect answer, or irrelevant incorrect answer. Cognitive biases were quantified as the Cognitive Bias Index (B_{ix}), which is essentially analogous to the discrimination index, with a higher B_{ix} indicating a stronger tendency to adhere to cognitive biases. Thus, $B_{ix} = (N_b - N_c)/(N_b + N_c)$, where N_b and N_c are the number of biased incorrect answers and correct answers, respectively. Participants were asked to answer all 5 questions within 3 minutes.

Second, cognitive biases in economic decision=making were examined using a questionnaire consisting of 2 questions, Q1 and Q2 below, based on the prospect theory of economic decision-making (Tversky and Kahneman, 1981; Kahneman, 2011).

Q1. In the following conditions, would you like to bet on a tossing coin game at a 50% probability of win/lose?

Q1-1: On the tail, you lose 10 000 Japanese Yen (JPY). On the head, you get 20 000 JPY.

(a) Yes, I do. (b) No, I don't.

Q1-2: On the tail, you lose 20 000 JPY. On the head, you get 2 000 000 JPY.

(a) Yes, I do. (b) No, I don't.

Q2. You are going to bet on a tossing coin game at a 50% probability of win/lose. If you lose 10, 100, 1,000, 10 000, 100 000, or 1 000 000 JPY at a loss, how much money would you like to get at a win in each condition of the loss?

These 2 questions are aimed to assess risk aversion. Q1 is further divided into 2 sub-questions, Q1-1 and Q1-2, each of which has a pair of choices, so that there are 4 possible combinations of the answers: *aa*, *ab*, *ba*, and *bb*. In both Q1-1 and Q1-2, "*a*" is risk taking and "*b*" is risk averse. Q1-1 assesses weaker risk aversion (the question with the lower-risk choice) and Q1-2 assesses stronger risk aversion (the question with the higher-risk choice). The percentage of participants who made each of these combinations of answers was quantified. In Q2, participants were asked to indicate how much money they wanted to gain at a win if they had to bet on a coin toss game with varying amounts of money that could be lost. The ratio of the amount from a win over a loss in each condition was calculated.

Modified Jumping-to-Conclusions Test

A computer-based psychological test was administered to examine the cognitive bias known as the jumping-to-conclusions bias—a tendency of decision-making with insufficient information gathering (Garety et al., 1991; Lincoln et al., 2010; Evans et al., 2012; Evans et al., 2015)—for which we modified the original version of the jumping-to-conclusions test used in other studies (Garety et al., 1991; Lincoln et al., 2010; Evans et al., 2012; Evans et al., 2015). In this modified jumping-to-conclusions test, 2 bottles containing 100 beads with red and blue colors in opposing ratios in each bottle were shown on the screen; for instance, when 1 bottle contained 60 red and 40 blue beads, the other bottle contained 40 red and 60 blue beads. Participants were instructed to draw beads 1 by 1 from only 1 of 2 bottles by clicking the button on the screen for up to 40 beads, without knowing from which bottle they were withdrawing. They were also explicitly told that every bead drawn was put back into the same bottle immediately after each withdrawal, so that the ratio was maintained and constant. Participants were asked which bottle they believed they had been assigned at any time while drawing beads in each trial. The instruction and 2 practical trials were given prior to starting the session, ensuring that the participants understood the test paradigm. A session comprised 40 trials, with varying ratios of 9:1, 8:2, 7:3, and 6:4 for 10 trials each. The sequence of beads drawn in each trial was predetermined pseudo-randomly in accordance with the ratio. The number of beads drawn at the time of the decision about which bottle, which reflects the jumping-to-conclusions bias, and percentages of correct choices of the bottle at each ratio were measured.

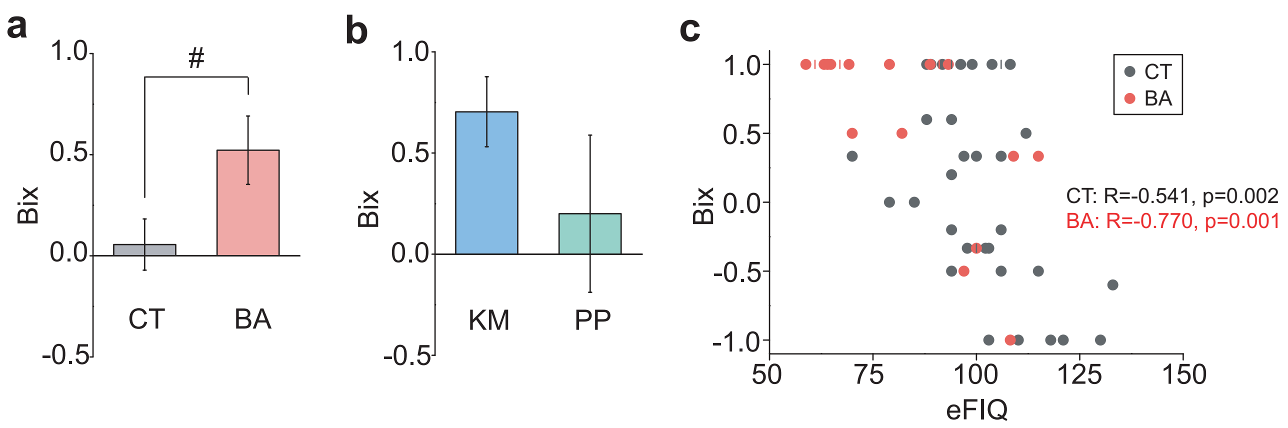

Figure 1. Assessments of cognitive biases with the extended version of the cognitive reflection test. Bar graphs showing comparison of the cognitive bias index (B_{ix}) between (A) BA and CT and between (B) KM and PP patients. # indicates statistical significance ($P < .05$) with the Mann-Whitney U-test, but not when eFIQ is adjusted with ANCOVA. Error bars indicate standard error of the mean. (C) A graph showing negative correlations between eFIQ and B_{ix} in both behavioral addicts and control subjects. The vertical line (|) indicates the data points that overlap. Abbreviations: BA, behavioral addicts; B_{ix}, Cognitive Bias Index; CT, control subjects; eFIQ, estimated full-scale intelligence quotient; KM, kleptomania; PP, paraphilia.

Functional Near-Infrared Spectroscopy

While participants were engaging in the modified jumping-to-conclusions test, PFC activity associated with the test was examined using fNIRS. The NIRO-200 NIRS Image Processing and Measuring System (Hamamatsu Photonics K.K.) was used in this study. There were 2 emitter probes (E1, E2; delivering laser pulses at the wave lengths of 775, 810, and 850 nm) and 8 detector probes (CH1-CH8), with the distance between an emitter and a detector (and thus, spatial resolution) at 3.0 cm, which enabled 10 points of recordings (R1-R10; Figure 4a). Oxygenated (oxy-Hb) and deoxygenated (deoxy-Hb) hemoglobin concentrations at the sampling rate of 0.5 Hz were recorded in the PFC, spanning over the left and right rostral dorsal PFC (corresponding to Brodmann Area 10/9/8), rostral dorsolateral superior PFC (Brodmann Area 10/9), caudal dorsomedial PFC (Brodmann Area 6/8), and caudal dorsolateral PFC (Brodmann Area 45/46/9) of the MarsAtlas (Auzias et al., 2016; Figure 4a). Since prolonged, slow oxy-Hb and deoxy-Hb changes were observed during the test, the area under the curve (AUC)—that is, summations of oxy-Hb and deoxy-Hb changes over time—were calculated at each recording site, and subsequent data analyses were conducted with the AUCs. Increased oxy-Hb concentrations coupled with decreased deoxy-Hb concentrations reflect neural activation, whereas decreases of both oxy-Hb and deoxy-Hb concentrations are thought to reflect neural inhibition (Villringer et al., 1993).

Data Analysis

Investigators who were not blinded to the experimental conditions conducted the data collection and statistical analyses. All statistical analyses were conducted using Statistica software (StatSoft, Tulsa, OK). A probability value of $P < .05$ was considered as statistically significance. Statistical analyses of the data were conducted using both parametric and non-parametric tests, depending on measurements. When an analysis of variance (ANOVA) was used for the analysis, the post hoc Tukey test was conducted for pair-wise comparisons. Since the eFIQ was significantly lower in behavioral addicts than control subjects (Table 1), when applicable, multivariate analysis of covariance (MANCOVA) and analysis of covariance (ANCOVA) were conducted for the analyses in the general linear model, with eFIQ as a covariate.

Data Availability

The data sets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Results

Subjects

The study recruited healthy control subjects (n = 31) and hospitalized patients with behavioral addictions (n = 16) who were diagnosed with gambling disorders (n = 1), kleptomania (n = 10) and paraphilia (n = 5; Table 1). The eFIQ of behavioral addicts was significantly lower than that of control subjects (unpaired t-test, $t_{44} = 3.47$; $P = .001$; Table 1).

Cognitive Biases

To investigate whether cognitive biases were different between behavioral addicts and control subjects, the extended version of the cognitive reflection test was conducted. Cognitive biases were quantified as B_{ix}, which was significantly higher in behavioral addicts than in control subjects (Mann-Whitney U-test; Z = 2.09; $P = .037$; Figure 1a), although B_{ix} was not different between kleptomania and paraphilia patients (Figure 1b). However, further analysis unveiled negative correlations that were present between B_{ix} and eFIQ in both behavioral addicts (Spearman's rank order correlation; R = –0.770; $P = .001$; Figure 1c) and control subjects (R = –0.541; $P = .002$; Figure 1c). Thus, a reanalysis of the data was conducted using an ANCOVA with the eFIQ as a covariate. This analysis revealed B_{ix} was not different between behavioral addicts and control subjects with controlling the eFIQ ($F_{1,43} = 0.030$ [$P = .864$] in behavioral addicts vs control subjects), suggesting that the higher B_{ix} in behavioral

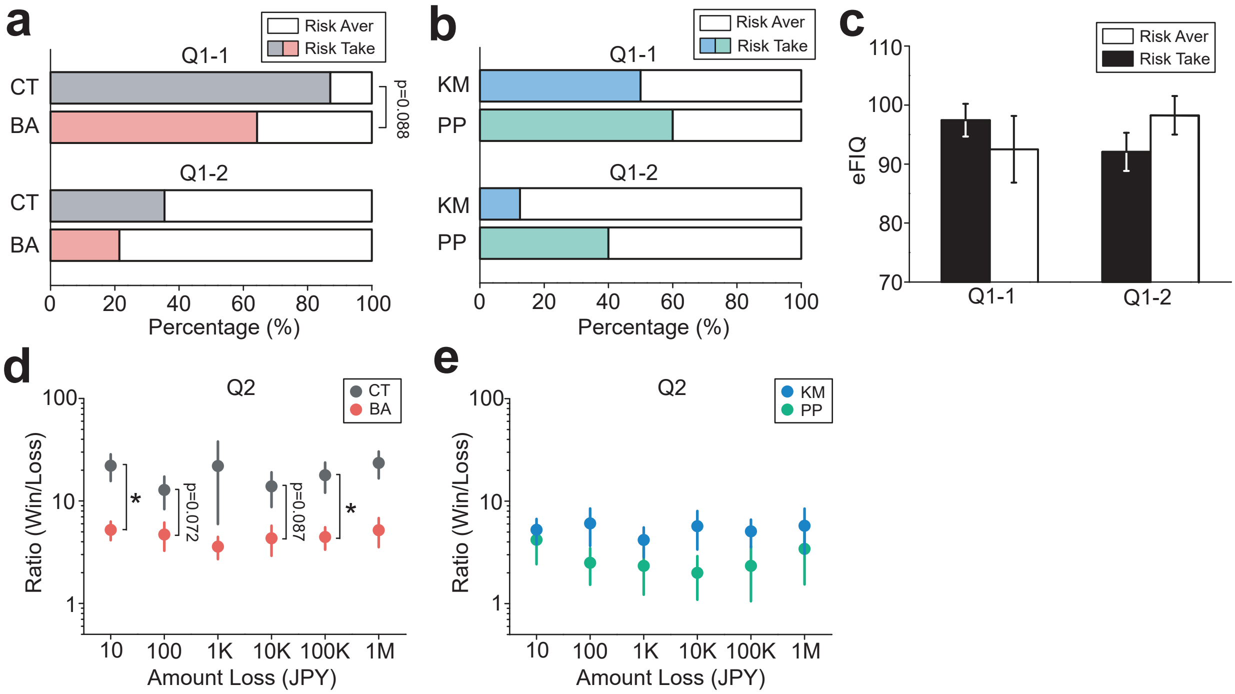

Figure 2. Assessments of cognitive biases in economic decision-making. Bar graphs showing percentages of (A) BA versus CT and (B) KM versus PP patients who made biased choices in Q1. "Risk Aver" and "Risk Take" indicate risk aversion and risk taking choices, respectively. (C) A bar graph showing a comparison of eFIQs for participants who made biased versus non-biased choices in Q1. Graphs showing the relationships between the amount of gain at the time of winning over the amount of loss at the time of losing in a bet, as rated by (D) BA versus CT and (E) KM versus PP patients. *P < .05. Abbreviations: BA, behavioral addicts; CT, control subjects; eFIQ, estimated full-scale intelligence quotient; KM, kleptomania; PP, paraphilia; Q, question; JPY, Japanese Yen.

addicts was primarily due to a lower eFIQ, rather than enhanced cognitive biases.

Higher Risk Taking in Economic Decisions

Studies have shown that people tend to exhibit biased choices to avoid risks under uncertainty, where probability judgments are required (Kahneman, 2011). Risk taking and aversion have typically been investigated in relation to economic decision-making. In this study, risk taking and aversion in economic decisions were assessed using the 2-question questionnaire with Q1 and Q2, relevant to economic decision-making (see Methods for the questionnaire).

First, the percentage of participants choosing answers for risk aversion (less risk taking) was examined with Q1, which was further divided into 2 sub-questions assessing weaker (Q1-1; the question with the lower risk choice) and stronger (Q1-2; the question with the higher risk choice) risk aversion. In these questions, lower percentages of behavioral addicts chose the risk aversion answer, as compared to control subjects, in the lower-risk question (Fisher exact test; P = .088; Figure 2a), but not the higher-risk question (P = .281; Figure 2a), suggesting that behavioral addicts tend to take more risks. No difference was observed in the percentages of kleptomania and paraphilia patients choosing the risk-aversion answer in these questions (Figure 2b). The eFIQ was also not different between those participants who were risk averse and those who were risk taking in their answers to these questions (Figure 2c), excluding the effects of an eFIQ difference on answering these questions in behavioral addicts and control subjects.

Risk aversion was examined in relation to the amounts of gains and losses of money during betting with question Q2, in which participants were asked to decide how much money they wanted the chance to win if they had to make a bet with a specific amount of money at risk for a loss, varying from a small (10 JPY, corresponding to approximately $0.1) to a large (1M JPY, corresponding to approximately $10 000) amount. In this question, behavioral addicts gave a significantly smaller amount needed from a win compared to a loss than control subjects when controlling for the eFIQ (MANCOVA with repeated measures; $F_{1,41}$ = 4.18 [P = .047] in behavioral addicts vs control subjects; $F_{5,205}$ = 0.780 [P = .565] in the amount at loss; $F_{5,205}$ = 0.337 [P = .890] in interaction; Figure 2d). Post hoc ANCOVAs that controlled for the eFIQ unveiled significant or marginally significant differences between behavioral addicts and control subjects in the loss amounts of 10 JPY ($F_{1,42}$ = 4.55; P = .039), 100 JPY ($F_{1,42}$ = 3.41; P = .072), 10 000 JPY ($F_{1,42}$ = 3.08; P = .087), and 100 000 JPY ($F_{1,42}$ = 4.07; P = .050; Figure 2d), suggesting that behavioral addicts tended to take more risks (make bets with a smaller amount available to win) than control subjects. No difference was observed between kleptomania and paraphilia patients in this question (Figure 2e).

These results suggest that behavioral addicts tend to take more risks on economic decisions than control subjects.

Impaired Probability Judgments

The jumping-to-conclusions bias was further examined using the modified jumping-to-conclusions test, along with simultaneously measuring PFC activity using fNIRS. In the modified jumping-to-conclusions test, participants were asked to guess from which 1 of 2 bottles with red and blue beads, mixed at varying ratios from 9:1 to 6:4, they were withdrawing the beads. The number of beads withdrawn at the time when participants made decisions to answer the

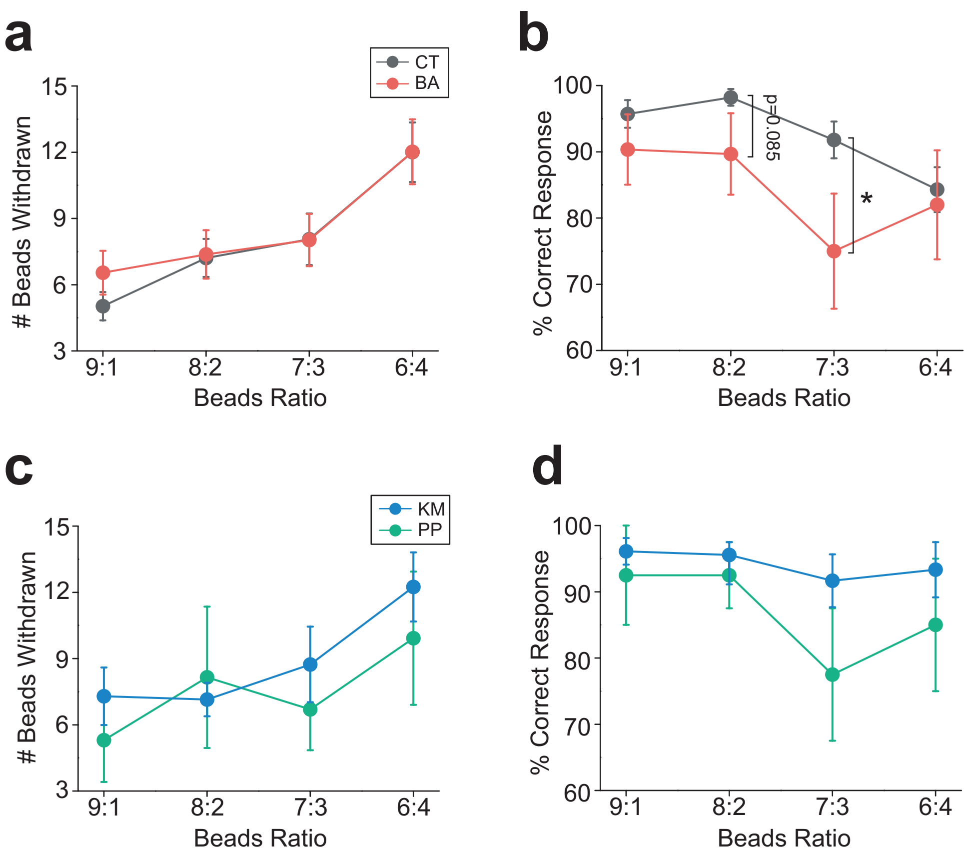

Figure 3. Assessments of the jumping-to-conclusions bias and probability judgment. (A) A graph showing a number of beads withdrawn by BA and CT until making the decision to choose the bottle under the variable bead ratios from 9:1 to 6:4 in the modified jumping-to-conclusions test. (B) A graph showing the percentage of correct choices under the variable bead ratios. *P < .05. Similarly, there are graphs (C) showing the number of beads withdrawn and (D) the percentage of correct choices in KM and PP patients. Abbreviations: BA, behavioral addicts; CT, control subjects; KM, kleptomania; PP, paraphilia.

question of which bottle is thought to reflect the jumping-to-conclusions bias: a tendency of making conclusions with insufficient information.

The number of beads withdrawn at the time of decisions was significantly increased in both behavioral addicts and control subjects when the ratio of beads changed from 9:1 to 6:4 (Figure 3a). However, there was no difference in the number between behavioral addicts and control subjects, even after controlling the eFIQ (Figure 3a). Percentages of correct responses were significantly or marginally significantly lower in behavioral addicts than control subjects when ANCOVA was conducted with the number of beads withdrawn as a covariate at the ratios of 8:2 ($F_{1,40}$ = 3.11; P = .085) and 7:3 ($F_{1,40}$ = 5.38; P = .026; Figure 3b), indicating that behavioral addicts made more incorrect responses, even though they withdrew as many beads as control subjects did. An ANCOVA with eFIQ as a covariate resulted in no difference in the percentages of correct responses between behavioral addicts and control subjects, excluding the effects of eFIQ on this test. Neither the number of beads withdrawn (Figure 3c) nor the percentage of correct responses (Figure 3d) was different between kleptomania and paraphilia patients.

These results suggest that behavioral addicts exhibit a similar jumping-to-conclusions bias as control subjects, but exhibit impaired probability judgments, so that behavioral addicts have difficulty in predicting outcomes based on probabilistic events.

Compromised Prefrontal Cortex Activity Associated with the Probability Judgments

Given that previous studies have demonstrated that PFC activity is associated with the jumping-to-conclusions bias (Lunt et al., 2012), we investigated oxy-Hb and deoxy-Hb changes in the PFCs of behavioral addicts and control subjects, using fNIRS during the modified jumping-to-conclusions test, to address whether the differences in test performance between the groups was reflected in the neural activity of the PFC (Figure 4a).

Throughout the test, significant decreases in the AUCs of oxy-Hb (recording sites R4 and R5 in Figure 4a) and deoxy-Hb (R5, R6, R7, R8, and R9) were observed in control subjects, primarily in the medial parts of the PFC in the right hemisphere, whereas such oxy-Hb and deoxy-Hb changes were essentially absent in behavioral addicts (Figure 4b–d). When the AUCs of oxy-Hb and deoxy-Hb were separately analyzed at different bead ratios, ratio-dependent increases of oxy-Hb and deoxy-Hb concentrations were observed in behavioral addicts, but not control subjects, in the recording sites R8 and R10, corresponding to the rostrolateral parts of the right PFC (2-way ANOVA with repeated measures; $F_{1,31}$ = 0.031 [P = .862] in Group; $F_{3,93}$ = 3.79 [P = .013] in Ratio; $F_{3,93}$ = 4.08 [P = .009] in interaction for oxy-Hb at R10; $F_{1,33}$ = 6.23 [P = .018] in Group; $F_{3,99}$ = 4.79 [P = .003] in Ratio; $F_{3,99}$ = 3.93 [P = .011] in interaction for deoxy-Hb at R8; $F_{1,30}$ = 0.390 [P = .537] in Group; $F_{3,90}$ = 3.29 [P = .024] in Ratio; $F_{3,90}$ = 3.40 [P = .021] in interaction for deoxy-Hb at R10; Figure 5a–c).

Correlations (Person's r) in the AUCs of oxy-Hb and deoxy-Hb in pairs of recording sites were further investigated (Figure 6a–e).

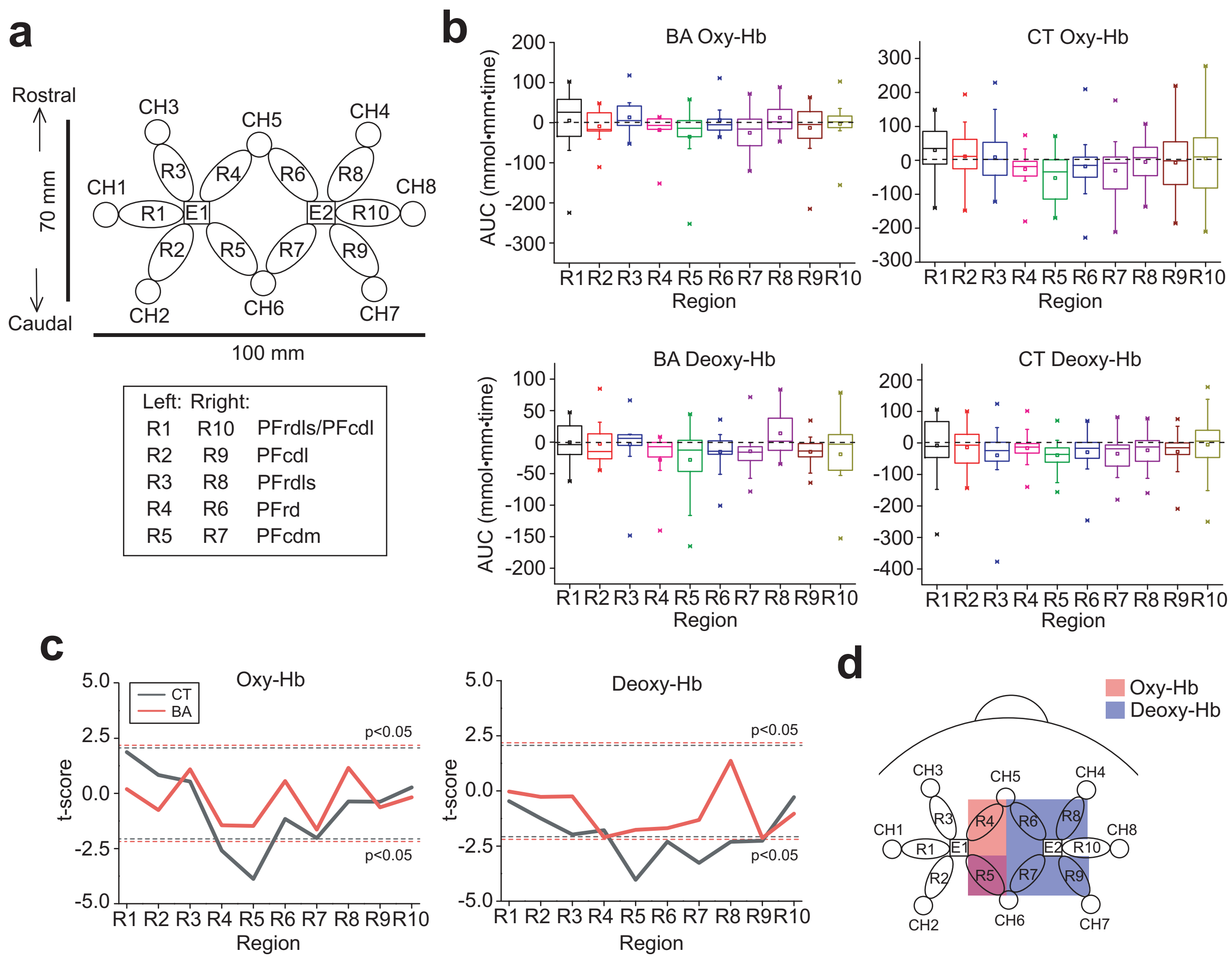

Figure 4. The fNIRS measurements of PFC activity during the modified jumping-to-conclusions test. (A) A schematic diagram illustrating the emitter (E1, E2) and detector (CH1–CH8) probe locations and the recording sites (R1–R10) on the skull. The box below the diagram indicates PFC subregions approximately corresponding to each recording site. (B) Graphs showing oxy-Hb and deoxy-Hb changes expressed as the AUC throughout the test at each recording site in BA and CT. (C) Graphs showing the t-scores of oxy-Hb (left) and deoxy-Hb (right) changes at each recording site. The dashed lines indicate the thresholds above or below which t-scores are statistically significant ($P < .05$). (D) Color illustrations of the recording sites where significant oxy-Hb (red) and deoxy-Hb (blue) changes were observed during the test. The site of overlapping significant oxy-Hb and deoxy-Hb changes is shown as purple. Abbreviations: AUC, area under the curve; BA, behavioral addicts; CT, control subjects; deoxy-Hb, deoxygenated; fNIRS, functional near-infrared spectroscopy; PFC, prefrontal cortex; oxy-Hb, oxygenated.

Correlations of oxy-Hb in both behavioral addicts and control subjects attained normal distributions, with the peaks around r = 0 in the histograms (Figure 6a–e). In behavioral addicts, however, a slightly broader distribution was observed as compared to control subjects, suggesting that more focused correlations may be present on the specific pairs of recordings sites in control subjects, as compared to behavioral addicts (Figure 6c–e). Correlations of deoxy-Hb in pairs of recordings sites of both behavioral addicts and control subjects also had normal distributions, with the peaks around r = 0 (Figure 6c–e).

Collectively, these results suggest that PFC activity in the right hemisphere is primarily associated with probability judgments in the modified jumping-to-conclusions test, and that these deficits are involved in behavioral addiction.

Discussion

In this preliminary study with a relatively small sample size, we have shown that behavioral addicts exhibit higher risk taking than control subjects, and show compromised probability judgments. In contrast, cognitive biases themselves are not substantially different between behavioral addicts and control subjects; although more biased responses were observed in the extended version of the cognitive reflection test in behavioral addicts than control subjects, this observation was primarily due to a significant difference of eFIQ. In economic decision-making, behavioral addicts were less risk averse in uncertain conditions than control subjects. Moreover, the number of beads withdrawn in the modified jumping-to-conclusions test was not different between behavioral addicts and control subjects, indicating no difference in the jumping-to-conclusions bias between behavioral addicts and control subjects. However, behavioral addicts were worse at making probability judgments to estimate the outcomes (choose the correct bin) based on probabilistic events (beads withdrawn). Collectively, an emerging picture from these results shows that behavioral addiction may be characterized by compromised probability judgments, which in turn lead to higher risk taking, primarily due to deficits in the second signal of the dual process model, whereas the first signal remains relatively intact. This is supported by

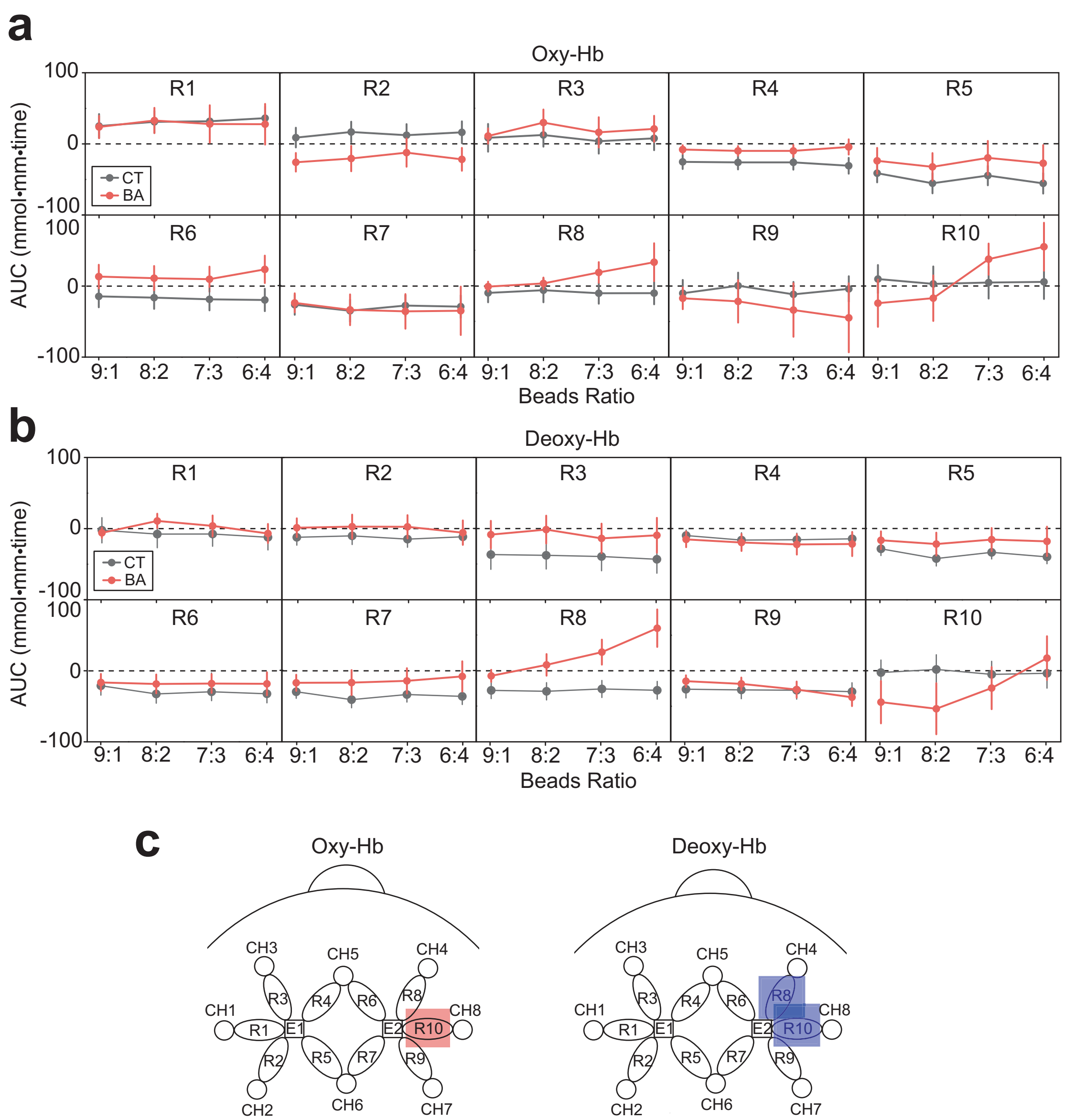

Figure 5. The fNIRS measurements of PFC activity at the different ratios of the modified jumping-to-conclusions test. Graphs showing (A) oxy-Hb and (B) deoxy-Hb changes at each recording site in BA and CT under the different bead ratios, ranging from 9:1 to 6:4. (C) Schematic diagrams of the recording sites with color illustrations where significant oxy-Hb (red) and deoxy-Hb (blue) changes were observed. Abbreviations: AUC, area under the curve; BA, behavioral addicts; CT, control subjects; deoxy-Hb, deoxygenated; fNIRS, functional near-infrared spectroscopy; PFC, prefrontal cortex; oxy-Hb, oxygenated.

fNIRS recordings of PFC activity, which is thought to play a central role in the second signal (Satpute and Lieberman, 2006). Our study unveiled that PFC activity in the right hemisphere is associated with performance on the modified jumping-to-conclusions test. The PFC activity observed in control subjects was absent in behavioral addicts, suggesting that deficits in this brain region may be involved in impaired probability judgments in behavioral addiction.

There are several major limitations in this study. The first and most obvious issue is that this study was conducted with a small sample size (n = 16 for behavioral addicts). Moreover, behavioral addicts were heterogeneous in their diagnoses and were further divided into groups of even smaller sizes, so that the current results should be cautiously interpreted as preliminary evidence. Another limitation is significant differences in intelligence levels between behavioral addicts and control subjects. We conducted statistical analyses, such as ANCOVA and MANCOVA with the eFIQ as a covariate, to account for such differences of intelligence level, and found that such differences of intelligence level significantly affected performance on some tests. Increasing the sample numbers in a future study would eventually enable the comparison of behavioral addicts and control subjects without considering such intelligence level differences.

Kleptomania and paraphilia patients were recruited in this study as part of the behavioral addiction group. We investigated whether there were any differences between kleptomania and paraphilia patients in the tests used in this study, to further characterize subtypes of behavioral addiction. To our knowledge, no previous study has compared cognitive and affective functions directly between these 2 subtypes of behavioral addiction. On average, it appears that there were differences between kleptomania and paraphilia patients, with paraphilia patients exhibiting lower B_{ix}, more risk taking, and fewer correct

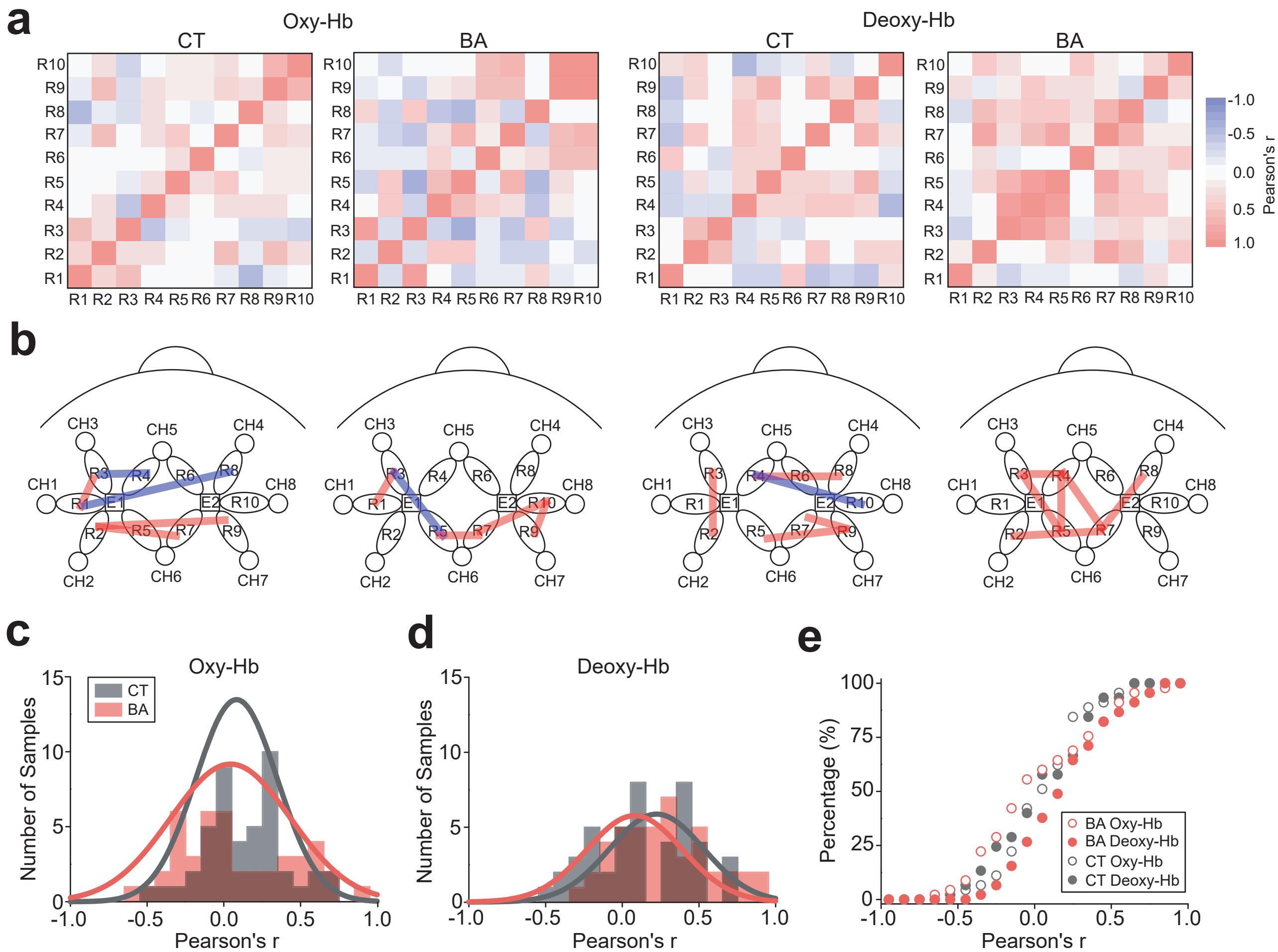

Figure 6. Correlations of oxy-Hb and deoxy-Hb changes within the PFC during the modified jumping-to-conclusions test. (A) Heat maps illustrating correlations (Pearson's r) of oxy-Hb and deoxy-Hb changes in all pairs of the recording sites. (B) Schematic diagrams illustrating correlations in pairs of the recording sites with statistically significant P values ($P < .05$). Positive and negative correlations are illustrated with the red and blue lines, respectively. Histograms with Gaussian fits for (C) oxy-Hb and (D) deoxy-Hb correlations, and (E) a cumulative histogram of them, illustrating distribution patterns of Person's r in BA and CT. Abbreviations: BA, behavioral addicts; CT, control subjects; deoxy-Hb, deoxygenated; PFC, prefrontal cortex; oxy-Hb, oxygenated.

responses in the modified jumping-to-conclusions test than kleptomania patients. However, due to the small sample size, the variances were too large, especially in paraphilia patients, and none of measurements reached statistical significance; therefore, no difference between them is conclusive at this moment. Comparisons between kleptomania and paraphilia patients with larger sample sizes in a future study may unveil the differences between these subtypes of behavioral addiction.

Previous studies have investigated decision-making in behavioral addiction. However, these studies were conducted in patients with gambling disorders as a prototypical sector of behavioral addiction, and primarily focused on impulsivity (Goodie and Fortune, 2013; Ligneul et al., 2013; Ioannidis et al., 2019). Thus, behavioral addictions other than gambling disorders, such as kleptomania and paraphilia, and decision-making and judgments other than the aspect of impulsivity, such as risk taking and probability judgment, have remained less explored. Few studies, if any, have examined cognitive biases with the extended version of the cognitive reflection test and the modified jumping-to-conclusions test in gambling disorders, such that whether performance on these questionnaires and psychological tests are also different from control subjects in patients with gambling disorders remains unclear. In gambling disorders, impaired probability judgments have been reported (Madden et al., 2009; Andrade and Petry, 2012; Linnet et al., 2012; Wiehler and Peters, 2015); this is somewhat consistent with our current study, which demonstrates that impaired probability judgments are also observed in kleptomania and paraphilia patients. In contrast, risk taking has been reported inconsistently in gambling disorders, with some research reporting more risk taking (Ligneul et al., 2013) and other data showing slightly more risk aversion (Branas-Garza et al., 2007). Cognitive biases are bestowed on various aspects of psychological processes, including the bias on self-recognition, such as in Dunning-Kruger effects (Kruger and Dunning, 1999). Although our current study did not unveil a clear difference in cognitive biases between behavioral addicts and control subjects, it is still possible that only some, but not all, aspects of cognitive biases may be compromised in behavioral addiction. Moreover, affective states influence cognitive biases, and vice versa (Harding et al., 2004; Hallion and Ruscio, 2011). Since heightened negative affects, such as stress, anxiety, and depressive moods, have been reported in behavioral addicts (Blaszczynski and McConaghy, 1989; Akin and Iskender, 2011; Alavi et al., 2012), augmented cognitive biases by heightened negative affects may be involved in behavioral addiction.

In this study, we investigated the neural correlates of performance on a modified jumping-to-conclusions test using fNIRS. We found that the right PFC was primarily involved in this test. In particular, decreases of oxy-Hb and deoxy-Hb concentrations were observed in the medial PFCs of control subjects, but such changes were absent in behavioral addicts. Ratio-dependent increases of oxy-Hb and deoxy-Hb concentrations were observed in the right rostrolateral PFCs of behavioral addicts, but not control subjects, which may partly be owing to the ceiling effect: that is, the test was too easy for control subjects to work even at the most difficult condition of a 6:4 ratio. A study has reported that the left PFC is associated with the jumping-to-conclusions bias in adult subjects with attention deficit/hyperactivity disorder (Lunt et al., 2012). Thus, our findings are strikingly different from this previous study. However, our study unveiled deficits not in the jumping-to-conclusions bias, but in probability judgments in behavioral addicts. Thus, it is possible that the jumping-to-conclusions bias and probability judgments are separately associated with the left and right PFC, respectively.

In conclusion, our preliminary study provides novel insight into characteristics of behavioral addiction pertaining to probability judgments and consequent risk taking, which may be associated with an impaired second signal but relatively intact first signal in the dual-process model. The further characterization of cognitive and affective processes with a larger sample size of behavioral addicts will help in establishing the criteria for including impulse-control disorder as a behavioral addiction, and understanding its neural mechanisms.

Acknowledgments

The authors thank staff members of the CRCT team in Kyowa hospital for support and thank all participants for enabling this study.

YA, MW, and YG conceived of the research. YA and YG analyzed the data and wrote the manuscript. All authors performed experiments, discussed the results, and contributed to the final manuscript.

This study was supported by research grants from the Kyoto University Foundation, ISHIZUE 2020 of Kyoto University Research Development Program, Institute of Seizon and Life Sciences, and Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Challenging Exploratory Research (19K22511).

Statement of Interest

The authors declare no financial and non-financial conflict of interest.

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