# Mock crime application of the concealed information test using fNIRS combined with SCR, HR and RT

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## Abstract

To explore the forensic application of neuroimaging-based concealed information test (CIT) with combined multiple measurements, the simultaneously recorded data of functional near-infrared spectroscopy (fNIRS), skin conductance responses (SCRs), heart rate (HR), and reaction time (RT) is collected in order to detect participants' concealed information in a standard CIT with a mock crime scenario. We hypothesized the fNIRS-based neuroimaging data could successfully detect deception, and the combination of multiple indicators could integrate multidimensional information triggered by deception, thus providing enhanced efficiency in deception detection. The results validated the hypotheses that fNIRS-based neuroimaging data could effectively discriminate between guilty and innocent participants after a mock crime. Furthermore, the use of multiple indicators resulted in a much higher detection efficiency (AUC = 0.96 with fNIRS channel 8) compared to the use of a single indicator (AUC = 0.66-0.86). These results illustrate the potential of the combination of fNIRS and multiple indicators for deception detection with a mock crime scenario and further facilitate the forensic application of fNIRS-based CIT.

## Introduction

It has been demonstrated that both physiological measurements and brain imaging technology, which mainly reflect activities of the autonomic nervous system (ANS) and the central nervous system (CNS) respectively, were valid for detecting one’s concealed information (Gamer et al., 2007; Gronau et al., 2005; Lin et al., 2018; Sai et al., 2014; Verschuere et al., 2010). Researchers have also suggested that the integration of multiple physiological measurements, as well as combining ANS/CNS measurements, leads to incremental validity in deception detection (Ambach et al., 2010; Bhutta et al., 2015; Gamer et al., 2008; Gamer & Berti, 2010; Kozel et al., 2009; Matsuda et al., 2009). The superiority of combining multiple measurements lie in that it not only reduces the random error compared to single measurements, maintaining the improved stability of deception detection (Gamer et al., 2007; Kozel et al., 2009; Matsuda et al., 2011; Wang et al., 2022). But could also integrate multidimensional information triggered by deception (i.e., the concealed information), and provide enhanced efficiency in deception detection (Klein Selle et al., 2016; Wang et al., 2022). Further, it’s also essential to explore the forensic application of deception detection with multiple indicators. Therefore, in the current study, we intend to combine brain imaging, physiological, and behavioral measurements for detecting concealed information in a mock crime scenario. The high deception detection efficiency was expected by combing functional near-infrared spectroscopy (fNIRS), skin conductance responses (SCR), heart rate (HR), and reaction time (RT) data.

The concealed information test (CIT) has a long-standing and noteworthy history in the domain of deception detection and has been widely utilized since its inception (Lykken, 1959, 1960). In Japan, the CIT has been successfully applied to practical criminal investigations on a large scale (Osugi, 2011). When implemented in mock crime scenarios, in the CIT, participants are instructed to respond to specific crime-related details (probe items, e.g., the type of weapon used in a murder, a knife) and other irrelative alternatives (irrelative items, e.g., a gun, a rope, a bat, an ice pick). Guilty individuals, who are previously familiar with this crucial piece of information, then be able to differentiate between crime-related and irrelative alternatives. And the discrepancy between the above responses could be detected through behavioral, physiological, or neuroimaging measurements (Gamer et al., 2007; Rosenfeld, 2019). Indeed, CIT has been extensively employed with autonomic measurement and electroencephalogram (EEG) and has demonstrated its significant efficacy in detecting deception (Ben-Shakhar & Elaad, 2003; Matsuda et al., 2011; Rosenfeld et al., 2006; Sai, Lin, et al., 2014; Varga et al., 2014).

With the development of brain-based neuroimaging technology, such as functional magnetic resonance imaging (fMRI), neuroimaging techniques can now easily locate the specific brain regions activated in tasks, making it possible to investigate the neural correlates underlying deception (Langleben et al., 2002; Logothetis & Wandell, 2004). Prior neuroimaging researches have primarily employed the differentiation of deception paradigm (DDP) to identify the neural correlates of deception, through construction and direct comparison of deceptive/truthful responses (Davatzikos et al., 2005; Gamer, 2014; Ito et al., 2011; Kozel et al., 2009). With the DDP, participants are typically required to answer questions (usually simple semantic or autobiographic questions) either truthfully or falsely. By systematically comparing patterns of truthful and deceptive responses, researchers can elucidate the brain activities implicated in this discernment (Gamer et al., 2007; Meijer & Verschuere, 2017). Although numerous researches have focused on exploring the neural mechanisms of deception, the potential use of neuroimaging tools for deception detection has not received adequate attention. Although Gamer et al. (2007, 2012) and Suchotzki et al. (2015) applied fMRI to identify the neural correlates of the classic deception detection paradigm CIT and found that neuroimaging-based deception detection mostly depends on the mental process of response inhibition. Only a limited number of researches have utilized fMRI with the CIT paradigm to conduct deception detection and have reported on its detection efficiency (Ganis et al., 2011; Hsu et al., 2019; Nose et al., 2009; Peth et al., 2015). For example, Ganis and colleagues (2011) conducted a classic three-stimuli CIT in the fMRI scanner to test whether fMRI could discriminate participants with certain concealed information (i.e., exact date) from those innocent participants. Their results found that the fMRI-based CIT could detect deception with an accuracy of 100% using ventrolateral and medial prefrontal cortex (mPFC) activities, whereas the detection accuracy would be largely injured if participants use trained countermeasures. Hsu et al. (2019) also conducted a similar CIT in an fMRI scanner, but using different digits as probe/irrelevant/target stimuli, and adopted a mental countermeasure. They reported over 0.80 detection efficiency when adopting different PFC activity, and almost unchanged 0.79 detection efficiency with mental countermeasure. Taken together, these findings serve to highlight the reliability of brain-imaging technology when utilized in the concealed information test.

Recently, functional near-infrared spectroscopy (fNIRS), an alternative instrument for brain-based neuroimaging, has lately obtained preference in many neuroimaging research (Dai et al., 2018; Hyde et al., 2018; X. Lin, Lei, et al., 2018; X. A. Lin et al., 2021; Zhang et al., 2021). Compared to fMRI, fNIRS is more portable, resilient against motion artifacts, costs less, imposes fewer restrictions, and is suitable for a wider range of people (Ding et al., 2013; Ferrari & Quaresima, 2012). Thus, fNIRS might be an alternative neuroimaging technique with more potential for deception detection application, as the discrepancy between deception and truth could be discriminated against through distinct hemodynamic changes. For instance, previous researches have shown increased hemodynamic activities in PFC when people are exposed to crime-related stimuli rather than irrelevant stimuli (Ding et al., 2013; Wang et al., 2022). However, only a limited number of studies have employed fNIRS in CIT with mock crime scenarios, which is a more natural way to let participants connect certain stimuli with a real crime process, to test its potentials for deception detection (Sai, Zhou, et al., 2014). Therefore, there is still insufficient evidence to support its practical applications and more empirical researches are needed.

Regarding deception detection through physiological means, skin conductance responses (SCRs), and heart rate (HR) are commonly used in psychological measurements (Ben-Shakhar & Elaad, 2003; Farahani & Moradi, 2013; Gamer et al., 2007, 2008; Klein Selle et al., 2017). These measurements reflect the activities of ANS and recently been considered to signify different theoretical underpinnings of the CIT (Klein Selle et al., 2016; Klein Selle & Ben-Shakhar, 2023). For instance, SCR may be explicable by the orienting response (OR), and those guilty participants are expected to elicit greater SCR when encountering crime-related stimuli compared to the irrelevant stimuli. While HR can be accounted for by the inhibition theory, thus those guilty participants are expected to elicit decreased HR in crime-related stimuli rather to the irrelevant stimuli. In addition, it is worth mentioning that RT is also regarded as an alternative behavioral indicator for distinguishing participants with and without crime-related knowledge (Suchotzki et al., 2017). The underlying mechanism of reaction time is often attributed to cognitive load (Verschuere et al., 2011; Vrij et al., 2006), which assumes that deception requires a greater cognitive resource, resulting in a longer reaction time compared to truth-telling.

Furthermore, since adopting multiple indicators in CIT can reduce random error and enhance classification results, previous researches have demonstrated that CIT's physiological measures could discriminate between guilty and innocent with fine accuracy, and could further be combined with other measurements, obtaining much better detection efficiency (Gamer et al., 2008; Wang et al., 2022). Therefore, we hypothesize that 1) higher hemodynamic responses, longer reaction time, increased SCR, and decelerated HR to the probe items than irrelevant items were expected only for guilty participants, but not innocent participants. 2) All measurements including fNIRS neuroimaging data, RT, SCR, and HR could effectively distinguish between guilty and innocent participants. 3) The combination of fNIRS, SCR, HR, and RT measurements can enhance deception detection efficiency to a higher level to detect concealed crime-related information in this mock crime CIT.

## Method

### Participants

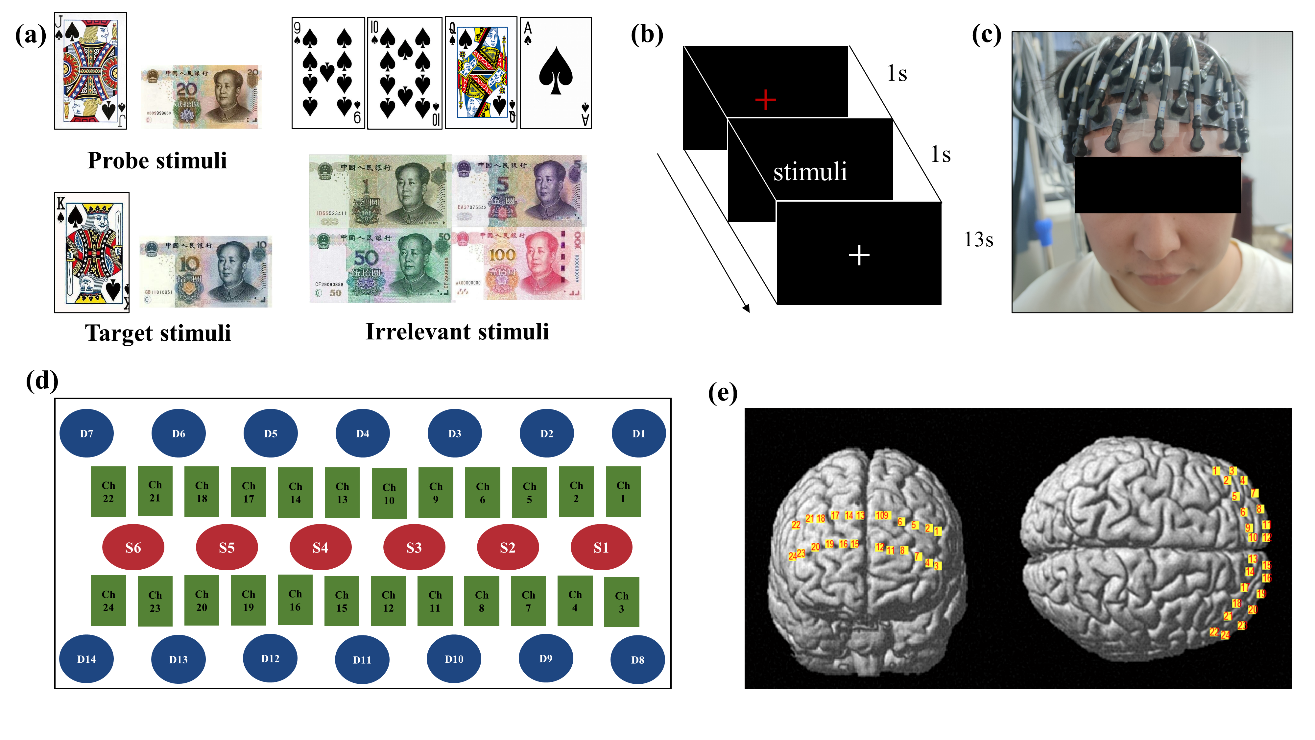
Sixty right-handed undergraduate/graduate students with normal or corrected-to-normal vision were recruited in this study. One of them was excluded for the low signal quality of the fNIRS data, while two participants were excluded for the non-responsivity of the SCR data. After exclusion, 57 participants remained (28 guilty group participants; 29 innocent group participants), **ranging in age from 17 to 24** (30 females; *M* = 19.8, *SD* = 1.6). None of them had a history of neurological or psychiatric disorders. The study was conducted under guidelines approved by the ethics committee of Hangzhou Normal University.

### Procedure

This study was conducted with two interrelated sub-tasks: Task 1 was a mock crime task; Task 2 was a CIT task with multi-measurements. The purpose and procedure of this study were explained to all participants upon their initial arrival at the laboratory, followed by a random distribution (draw lots) of participants into the guilty or innocent group.

In task one, participants from the guilty group committed a mock crime by being instructed to steal some valuable items from a laboratory. Participants were unknown about what they needed to steal but were just instructed to find and take them out like real stealers. In the laboratory, an envelope containing a banknote valued 20 RMB (about 3.2 US dollars, probe1) and the Jack of Spades (probe2) could be found in the bottom drawer of a table, and participants were instructed to hide what they steal in their pocket throughout the entire experiment. To make sure that participants memorized the probe item correctly, an additional memory check was conducted after the mock crime. But for those participants from innocent group, they were asked to visit the same laboratory room without committing any crime. What's more, a paper of notification about another theft crime was provided to all participants, indicating that someone entered the same laboratory, opened the drawer, and stole an envelope containing a banknote valued 10RMB and a King of Spades, which were used as target items in the following CIT. In order to make sure that all participants memorized the target stimuli, a memory check regarding the above theft crime was conducted at the end of task one.

In the following CIT (task two), there were three types of stimuli: Probes, Targets, and Irrelevants. Target items were a banknote valued 10RMB and a King of Spades (see Figure 1a for details), which were known by all participants through the theft crime notification. Probe items were a banknote valued 20RMB and the Jack of Spades, and only guilty group participants were exposed to them. Irrelevant items were four banknotes valued differently (1, 5, 50, and 100 RMB) and four playing cards (9, 10, Queen, and the Ace of Spades), which were unfamiliar to all participants. Before the CIT, all participants received a cover story, indicating that due to recent theft crimes, all people are required to undergo the lie detector examination to affirm their innocence. Participants were informed that in the CIT, they would be presented with different items and need to press the left or right button to indicate whether they recognized the items or not (the meaning of buttons was counter-balanced across participants). Stimuli were presented in a pseudo-random order to avoid the consecutive presentation of the same items. In the CIT, there were two probes, two targets, and eight irrelevant items and each of them was presented eight times. Accordingly, participants completed 96 (12×8) trials. At the beginning of each trial, a red fixation was presented for 1 s, and the stimulus item was presented for 1 s, followed by another fixation of 13 s (Figure 1b). In addition, if participants did not respond within 1 s, feedback (“TOO SLOW”) was presented for 4 s. The experiment ended automatically if the participants missed five responses. The whole experiment lasted for approximately 26 min.



**Figure 1.** (a) The probe, irrelevant and target stimuli presented in the CIT. (b) An example of a single trial of the CIT. (c) The head patch covering the prefrontal cortex of one participant. (d) The arrangements of optodes and channels for the fNIRS system (red circles represent sources, blue circles represent detectors, and green rectangles represent the fNIRS channels). (e) The estimated locations of the 24 fNIRS channels along the prefrontal cortex.

### Data acquisition for concurrent fNIRS and physiological recordings

For the fNIRS recordings, the experiment was performed using a continuous wave (CW6) fNIRS system (Techen, Inc., Milford, MA, USA) with six laser sources and fourteen optical detectors, generating 24 channels, which were able to detect the changes of oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentration in the prefrontal cortex. Optodes were symmetrically arranged in an area of 7×30cm², with the distance between each source and detector being 3cm (Figure 1c & d). The diffuse NIR light from each source through cortical regions was acquired at its nearest detectors, and 24 source-detector pairs (channels) in total were measured with a 25Hz sample rate. Probes were positioned according to international 10-20 coordinates, so the lowest optodes were aligned with Fp1- Fp2 line. The 3D-magnetic space digitizer Patriot Digitizer (Polhemus Inc., Colchester, Vermont, US) was also used to obtain 3D spatial information of each optode for a represented Chinese participant (head size 54). The NIRS-SPM software was used to estimate the 3D location in the Montreal Neurological Institute (MNI) space (Singh et al., 2005). 3D spatial coordinates of 24 channels are shown in Figure 1e.

For physiological recording, BIOPAC MP160 (BIOPAC Systems, Inc., Goleta, CA, United States) was used. SCR was measured using two Ag/AgCl electrodes (TSD203) filled with GEL101 that were placed on the phalanges of the index and middle fingers of the left hand. All the participants washed their hands prior to the attachment of the electrodes. ECG measurement was acquired by three electrodes placed in a lead II configuration: the negative electrode was placed below the right clavicle, the positive electrode on the left lower abdomen, and the ground electrode was placed on the right lower abdomen. BIOPAC MP160 system was set at 1Hz low-pass band for SCR signal and at 1-35Hz for ECG signals. SCR and ECG signals were sampled at 1000Hz using AcqKnowledge v. 5.0 (BIOPAC Systems, Inc., Goleta, CA, United States). E-prime 2.0 (Psychology Software Tools, Sharpsburg, PA) software was used to present stimuli.

### Data analysis

#### Behavioral data analysis

False responses (3% among total responses) and irregular responses (i.e., Z-scores of RT were larger than 3 or smaller than -3; 1.35% among total responses) were excluded. Then the CIT effect of RT (MRT\_*probes* – MRT\_*irrelevants*) was computed for subsequent RT analyses. Finally, an independent samples t-test was conducted to compare the CIT effect of RT between the guilty and innocent groups.

#### Physiological responses

For SCR data, AcqKnowledge v.5.0 (BIOPAC Systems, Inc., Goleta, CA, United States) was used to calculate the peak-to-peak amplitudes defined as the maximal change between the peaks (Yu et al., 2019). For each participant, the mean value of the peak-to-peak amplitude during 1-5 s was calculated. Participants whose standard deviation of the raw SCR scores was below 0.01 during the procedure were considered to be non-responders and the data were eliminated from all SCR analyses (Geven et al., 2018).

For ECG data, R waves and R peaks were detected and the distance between them was calculated with an artifact detection and rejection procedure (De Clercq et al., 2006; Klein Selle et al., 2016) using AcqKnowledge v.5.0 (BIOPAC Systems, Inc., Goleta, CA, United States) and MATLAB2018a (The MathWorks, Natick, MA, USA). Afterwards, the R-R intervals were converted to HR in beats per minute (bpm) per real-time epoch (1s). These second-by-second post-stimulus HR values were baseline-corrected by subtracting the average HR value in the 3-s preceding stimulus onset, resulting in 10 post-stimulus difference scores (△HR). Notably, The average of all △HR scores has been demonstrated to be better than the largest deceleration of all △HR scores as a detection measure (Gamer et al., 2008; Klein Selle et al., 2016, 2017).

The data from the two measurements were converted to a standard z-score to eliminate individual differences. The mean standard scores of the probe and irrelevant items of two measurements for each participant were calculated. Standard scores larger than 5 or smaller than -5 were discarded (Klein Selle et al., 2016).

#### fNIRS data analysis

The fNIRS data preprocessing was conducted using Homer2 software (Huppert et al., 2009). The raw data were converted to optical density changes and then converted to HbO and HbR concentration changes using the modified Beer–Lambert Law (Cope & Delpy, 1988). The HbO and HbR signals were processed using a low pass filter at 0.2 Hz followed by a high pass filter at 0.01 Hz. Only HbO signals were analyzed as the change in HbO is the most sensitive indicator of regional cerebral blood flow changes (Homae et al., 2007). The duration of each trial was 15 s which included 1 s period prior to the stimulus onset, 1s for stimulus presenting, and a 13 s for stimulus and recovery. We then calculated the run-averaged HbO concentration changes and the grand-averaged HbO data for the probe and irrelevant stimuli of the two groups. Finally, the mean values of 4-8, 5-9, and 3-11s of the run-averaged HbO data were extracted from each channel for each participant for statistical analysis. Since the results from these time windows were similar, 3-11s was chosen as the representative time window for fNIRS HbO changes for further analyses. All *p-*values of the *F*-test were corrected for a false-discovery rate (FDR, *p* < 0.05, Singh & Dan, 2006). All statistical analyses were conducted using SPSS 23.0. Also, the HbO signals were mapped using the BrainNet Viewer tool (Xia et al., 2013) to illustrate the brain imaging activity when encountering probe and irrelevant items for guilty and innocent participants.

## Results

### Behavioral results

The mixed ANOVA on error rates revealed a significant main effect of type, *F* = 5.88, *p* < 0.05, *η²* = 0.10, with a higher error rate for the probe stimuli compared to the irrelevant stimuli (4% ± 1% vs. 1.5% ± 0.2%). The main effect of group was also significant, *F* = 5.16, *p* < 0.05, *η²* = 0.09, with a higher error rate for the guilty group than the innocent group (3.8% ± 0.7% vs.1.7% ± 0.6%). However, the interaction of the stimulus type and the group did not reach significance, *F* (1,55) = 2.33, *p* > 0.05. The independent sample t-test on RT CIT effect revealed a significant difference between the guilty and innocent group, *t* (1,55) =5.48, *p* < 0.001, Cohen’s *d* = 1.48, with a significantly larger RT CIT effect in the guilty group than that in the innocent group (84.10 ± 8.94ms vs. 25.54 ± 5.99ms, see Figure2a).



**Figure 2.** (a) The CIT effect of reaction time (RT) to the probe and irrelevant items in the guilty and innocent groups. (b) The Z-scores of the skin conductance response (SCR) to the probe items of the guilty and innocent participants. (c) The Z-scores of heart rate (HR) to the probe items of the guilty and innocent participants.

Note: \* *p* < 0.05, \*\**p* < 0.01, \*\*\* *p* < 0.001.

### Physiological results

The z-scores of the peak-to-peak amplitude of the SCR and HR were averaged across the participants in the two groups (guilty vs. innocent). Independent sample t-tests were conducted for each physiological index with one between-subject variable (group: guilty vs. innocent). The dependent variables were the mean z-scores of two physiological indices within each group.

For peak-to-peak amplitude of SCR, the independent sample t-test indicated that there was a significant difference between the SCR in response to probe items between the guilty and innocent groups, *t* (55) = 4.73, *p* < 0.001, Cohen’s *d* = 1.25, indicating that the SCR to the probe item in the guilty group was significantly larger than that in the innocent group (Figure 2b).

For the HR data, the results of independent t-tests showed that there was a significant difference between the HR in response to probe items between the guilty and innocent groups, *t*(59) = -3.83, *p* < 0.001, Cohen’s *d* = -1.01. These results show that the HR response to the probe in the guilty group was significantly shorter than that in the innocent group (Figure 2c).

### fNIRS results

The averaged HbO signals of each channel for the probe and irrelevant stimuli from the guilty and innocent groups are shown in Figure 3 and Figure 4.

2 × 2 repeated measures ANOVAs were performed on the HbO signals using one within-subject variable (stimuli: probe vs. irrelevant) and one between-subject variable (group: guilty vs. innocent) and the results were presented in Table S1. Among the guilty group, it revealed a significant main effect of stimuli type in channels 1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24 (*Fs* ≥ 4.43, *ps* ≤ 0.04, *ηs²* ≥ 0.07, FDR corrected). However, for the innocent group, there was no significant main effect in 24 channels after FDR correction(*Fs* ≤ 5.93, *ps* > 0.05, FDR corrected). The results of analyses also revealed significant interaction between the stimuli type and the group in channels 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21）(*Fs* ≥ 8.00, *ps* ≤ 0.009, *ηs²* ≥ 0.13, FDR corrected, Table 1).

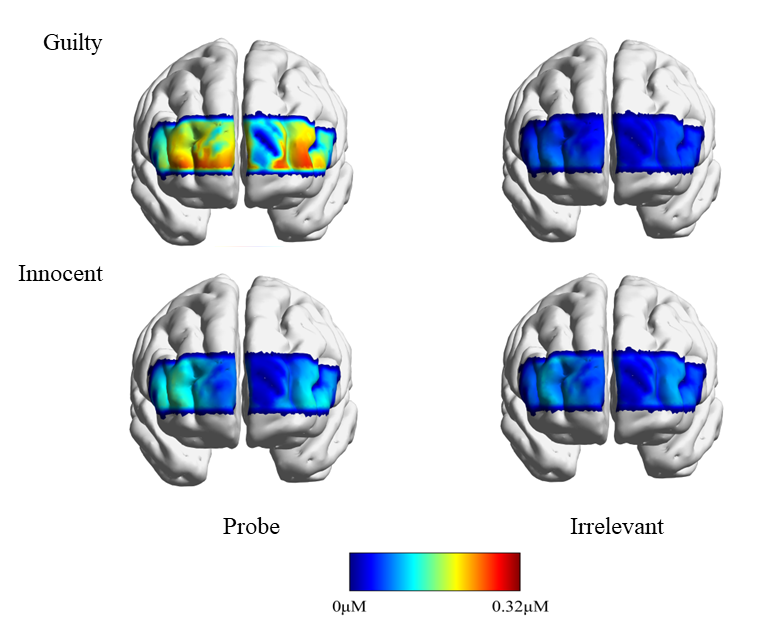
The results of simple effects analysis showed that participants in the guilty group exhibited significantly higher HbO concentration changes in response to the probe stimuli compared to that from irrelevant stimuli in channels 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21(*F*(1, 55) ≥ 8.06, *ps* ≤ 0.01, *ηs²* ≥0.11). To visualize the brain activity for probe and irrelevant stimuli conditions in the guilty and innocent groups, the HbO images were created and displayed on a brain template shown in Figure 4.

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| **Table 1**. Statistical analysis using fNIRS oxyhemoglobin (HbO) changes | | | | | | | |
| Channels | MNI coordinates | | | Brain regions | Probability | Group×Stimuli | AUC |
| X | Y | Z |
| Ch 5 | -46 | 43 | 26 | Left MFG (BA45) | 0.85 | *F* = 17.02\*\*\* | 0.81\*\*\* |
| Ch 6 | -35 | 55 | 28 | Left MFG(BA46) | 0.89 | *F* = 17.18\*\*\* | 0.81\*\*\* |
| Ch 7 | -48 | 51 | 0 | Left MFG(BA46) | 0.56 | *F* = 16.97\*\*\* | 0.82\*\*\* |
| Ch 8 | -38 | 63 | 0 | Left MFG (BA10) | 0.78 | *F* = 28.86\*\*\* | 0.86\*\*\* |
| Ch 9 | -22 | 61 | 29 | Left SFG(BA10) | 0.85 | *F* = 23.06\*\*\* | 0.85\*\*\* |
| Ch 10 | -10 | 65 | 31 | Left SFG(BA10) | 1 | *F* = 8.99\*\* | 0.83\*\*\* |
| Ch 11 | -25 | 69 | 2 | Left SFG (BA10) | 0.92 | *F* = 20.94\*\*\* | 0.82\*\*\* |
| Ch 12 | -8 | 73 | 1 | Left SFG (BA10) | 0.65 | *F* = 18.51\*\*\* | 0.80\*\*\* |
| Ch 13 | 10 | 67 | 29 | Right SFG (BA10) | 0.98 | *F* = 12.06\*\* | 0.86\*\*\* |
| Ch 14 | 22 | 64 | 28 | Right SFG (BA10) | 0.7 | *F* = 12.91\*\*\* | 0.77\*\*\* |
| Ch 15 | 11 | 74 | 0 | Right SFG(BA10) | 0.79 | *F* = 16.14\*\*\* | 0.78\*\*\* |
| Ch 16 | 26 | 70 | 0 | Right SFG(BA11) | 0.99 | *F* = 26.15\*\*\* | 0.85\*\*\* |
| Ch 17 | 34 | 58 | 27 | Right MFG (BA46) | 0.89 | *F* = 10.01\*\* | 0.77\*\*\* |
| Ch 18 | 45 | 50 | 26 | Right MFG (BA46) | 1 | *F* = 12.88\*\*\* | 0.78\*\*\* |
| Ch 19 | 38 | 65 | -1 | Right MFG(BA10) | 0.64 | *F* = 23.68\*\*\* | 0.83\*\*\* |
| Ch 20 | 47 | 56 | -2 | Right MFG(BA46) | 0.82 | *F* = 16.58\*\*\* | 0.79\*\*\* |
| Ch 21 | 53 | 39 | 25 | Right IFG (BA45) | 0.52 | *F* = 7.98\*\* | 0.74\*\* |

\* *p* < 0.05, \*\**p* < 0.01, \*\*\* *p* < 0.001



**Figure 3**. The time courses of the grand-averaged hemodynamic (HbO) changes associated with the probe (red solid curve) and irrelevant stimuli (blue solid curve) for the guilty (top) and innocent group (bottom) participants.



**Figure 4**. Mapping of the grand-averaged HbO concentration changes associated with the probe items for the guilty group (top left), the probe items for the innocent group (bottom left), the irrelevant items for the guilty group (top right), and the irrelevant items for the innocent group (bottom right). We found that in the guilty group, the probe items elicited higher hemodynamic responses than the irrelevant stimuli over the prefrontal cortex but not in the innocent group.

### Correlation analysis of fNIRS, physiological data, and RT data

Based on the Z-scores of the CIT effect (probe minus irrelevant), the correlation between fNIRS, physiological, and RT data of guilty and innocent groups was examined. The average Z-scores of HbO signals were used to investigate the correlation with the other indicators. The results revealed that there were no significant correlations between fNIRS, physiological, and RT data in either the guilty or the innocent group (averaged by channels, see Table 2).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 2**. Correlations between RT, SCR, HR, and fNIRS data | | | | | | | |
|  | Guilty group | | |  | Innocent group | | |
|  | SCR | HR | fNIRS |  | SCR | HR | fNIRS |
| RT | 0.14 | 0.12 | 0.20 |  | 0.18 | 0.03 | 0.07 |
| SCR |  | -0.08 | -0.07 |  |  | 0.20 | 0.11 |
| HR |  |  | 0.10 |  |  |  | 0.05 |

### Individual analysis using single and combined indicators

The receiver operating characteristic (ROC) analysis was performed utilizing fNIRS data, SCR, HR, and RT indicators to evaluate whether they could distinguish participants from guilty and innocent groups. Moreover, the diverse combination of the above indicators was also examined to assess whether they could work more effectively compared to single indicators. In this analysis, participants' groups (guilty or innocent) were set as state variables and standardized data from the different indicators were set as test variables. The ROC curves provided data reflecting the rate of "True positive" vs. "False positive" at varying decision thresholds for specific indicators. To compute the detection efficiency of various indicator combinations, each indicator would be equally weighted and merged into a single indicator (Hu et al., 2013), so as various channels of the fNIRS data.

The results demonstrated that all indicators, including fNIRS, SCR, HR, and RT, could discriminate guilty from innocent participants above a chance level. The RT measurement demonstrated a detection efficiency (AUC) of 0.86 (CI = [0.76-0.96], *p* < 0.001). Two physiological measurements, SCR and HR, can also effectively discriminate guilty from innocent participants (SCR: AUC = 0.66, CI = [0.52-0.80], *p* < 0.001; HR: AUC = 0.79, CI = [0.68-0.91], *p* < 0.01). The general detection efficiency of fNIRS (24 channels averaged) is 0.81 (CI = [0.70-0.93], *p* < 0.001). Regarding to every single significant channel indicator (see Table 1 for detailed single channel AUC), channel 8, located at the left MFG, obtained the highest AUC of 0.86 (CI = [0.76-0.95], *p* < 0.001).

Moreover, our results demonstrated the combination of diverse indicators could further improve the detection efficiency. When fNIRS (24 channels) was combined with the other indicators, the results showed that the relatively higher AUC was obtained (AUC = 0.93, CI = [0.88, 0.99], *p* < 0.001, see Table 3). Furthermore, when selecting the most distinguishing channel 8 as the represented fNIRS data, and combining the channel 8 data with other indicators, the result was the highest detection efficiency of 0.96 (CI = [0.91, 1.00], *p* < 0.001, see Table 3).

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| --- | --- | --- | --- |
| **Table 3**. Receiver operating characteristic (ROC) analyses and the area under the ROC curve (AUC) of the single and combined indicator | | | |
| Indicators | AUC | 95% CI | |
| Lower | Upper |
| SCR | 0.66\* | 0.52 | 0.80 |
| HR | 0.79\*\*\* | 0.68 | 0.91 |
| RT | 0.86\*\*\* | 0.76 | 0.96 |
| fNIRS (24 Channels) | 0.81\*\*\* | 0.70 | 0.93 |
| fNIRS & HR | 0.89\*\*\* | 0.81 | 0.97 |
| fNIRS & SCR | 0.80\*\*\* | 0.69 | 0.91 |
| fNIRS & RT | 0.89\*\*\* | 0.80 | 0.97 |
| fNIRS & HR & SCR | 0.90\*\*\* | 0.82 | 0.98 |
| fNIRS & SCR & RT | 0.87\*\*\* | 0.79 | 0.96 |
| fNIRS & HR & SCR & RT | 0.93\*\*\* | 0.88 | 0.99 |
| fNIRS (Ch 8) | 0.86\*\*\* | 0.76 | 0.95 |
| Ch 8 & HR | 0.92\*\*\* | 0.85 | 0.99 |
| Ch 8 & SCR | 0.88\*\*\* | 0.79 | 0.96 |
| Ch 8 & RT | 0.91\*\*\* | 0.83 | 0.98 |
| Ch 8 & HR & SCR | 0.93\*\*\* | 0.88 | 0.99 |
| Ch 8 & SCR & RT | 0.92\*\*\* | 0.84 | 0.99 |
| Ch 8 & HR & SCR & RT | 0.96\*\*\* | 0.91 | 1.00 |

\**p* < 0.05, \*\**p* < 0.01, \*\*\* *p* < 0.001

Note: RT = Reaction Time; SCR = Skin Conductance Response; HR = Heart Time.

## Discussion

In the current study, neuroimaging (fNIRS), physiological (SCR and HR), and behavioral (RT) data were simultaneously recorded and analyzed to distinguish guilty/innocent participants using a standard concealed information test with a mock crime scenario. Consistent with our hypothesis, we found that only the guilty participants showed greater brain activation in several brain regions (the bilateral MFG, the bilateral SFG, and the right IFG) based on fNIRS data in response to probe stimuli, along with longer RTs, larger SCRs, and smaller HRs compared to irrelevant stimuli, but not the innocent group participants (Klein Selle et al., 2016, 2017; Sai, Zhou, et al., 2014; Wang et al., 2022). What’s more, the ROC analysis showed that all of the indicators, including fNIRS-based brain imaging data, SCR, HR, and RT, could significantly discriminate guilty from innocent participants, with AUC ranging from 0.66 to 0.86. Moreover, our results demonstrated that combining fNIRS data (represented channel 8), SCR, HR, and RT can detect concealed crime-related information with an associated AUC of 0.96 (0.93 with all 24 fNIRS channels), suggesting the validity and potential of multi-indictors-based CIT for mock crime.

Our results revealed that RT could effectively discriminate the guilty group from the innocent group, consistent with previous studies (Hu et al., 2013; Kleinberg & Verschuere, 2015). As shown in Figure 2a, the CIT effect of RT was robust in the guilty group, yet not in the innocent group. Previous studies have demonstrated that the reaction time for deceptive responses is generally longer than for truthful responses because deception behaviors require more cognitive effort (Sartori et al., 2018; Suchotzki et al., 2017; Vrij et al., 2010). In the present study, guilty participants focused on proving their innocence, thus having to lie to deny the recognition of probe stimuli and tell the truth for irrelevant stimuli in the CIT. In contrast, innocent group participants responded truthfully when they denied recognizing both probes and irrelevant stimuli, as they indeed did not commit the crime. Thus, more cognitive effort was needed for the guilty participants to deny the recognition of probe stimuli compared to irrelevant stimuli, but not for innocent participants.

For the physiological measurements, we found significantly increased SCR and decreased HR for probe stimuli compared to irrelevant stimuli in the guilty group but not in the innocent group, also consistent with previous autonomic-based CIT studies (e.g., Klein Selle et al., 2016, 2017; Matsuda et al., 2009; Wang et al., 2022). According to the response fractionation model (Klein Selle et al., 2016, 2017; Klein Selle & Ben-Shakhar, 2023), the SCR reflects an Orienting Responses (OR), while the HR reflects Arousal Inhibition (AI). In particular, OR is elicited by novel, significant, and external stimuli, while AI represents the response one intentionally inhibits dominant physiological arousal induced by concealed crime-related stimuli. In the current study, the probe stimuli (a banknote valued 20 RMB and the Jack of Spades) stolen by the guilty participants were only meaningful and significant to them. Thus, larger SCRs to probe stimuli compared to irrelevant stimuli were found only in the guilty group, not in the innocent group. Similarly, the participants in the guilty group intended to inhibit their heart rate from hiding their recognition of the stolen probe items to avoid being detected when the probe stimuli were presented, which could explain the decreased heart rate.

For the fNIRS imaging results, we observed probe stimuli elicited significantly larger HbO changes compared to irrelevant stimuli in the bilateral MFG, the bilateral SFG, and the right IFG in the guilty group but not in the innocent group, which is consistent with previous studies (e.g., Gamer et al., 2012; Kozel et al., 2005, 2009; Langleben et al., 2005; Suchotzki et al., 2015). The bilateral MFG is generally accepted to be related to the function of response control (Barbey et al., 2013; Kozel et al., 2005; Mameli et al., 2010; Priori et al., 2008). In our paradigm, the probe stimuli could only be recognized by the person who committed the crime (i.e., the guilty participants). In the CIT, to show their innocence, the guilty participants needed to perform two cognitive processes: a) preventing themselves from conducting an intuitively honest response, and b) inhibiting their guilty knowledge to pretend their innocence. The former process required them to avoid admitting recognition of the two probe stimuli (i.e., the banknote valued 20RMB and the Jack of Spades) and make opposite responses (i.e., to press the button signifying “I do not recognize the item”), which is associated with the bilateral MFG and the function of response control (Mameli et al., 2010; Wang et al., 2022). The latter process required the guilty participants to hide their guilty knowledge and inhibit their pop-out honesty impulsion, thus is involved with a different function called inhibition control, which is related to the right IFG (Aron et al., 2004, 2014; Suchotzki et al., 2015). Additionally, we found activation in the bilateral SFG, which is believed to be related to goal-processing operations and planning of complex actions (Ding et al., 2014; Fincham et al., 2002; Hogeveen et al., 2022; Mansouri et al., 2017). This result is expected since the guilty participants have a consistent goal throughout the whole CIT including pretending not to know the crime-related probe items just as those innocent participants and behaving normally to other irrelevant items. The discriminative responses to those different stimuli need the involvement of the goal-processing and planning function in the current study, as well as the corresponding activation of the bilateral SFG, therefore seems reasonable.

Although the CIT paradigm for deception detection has been systematically applied in Japan for over ten years (Osugi, 2011), the neuroimaging-based CIT has a long way to go for forensic application. As one of the most typical neuroimaging tools, fMRI has a long history of being used for discovering the neural mechanism of deception (Ganis et al., 2009; Langleben et al., 2002). Prior studies have typically employed the differentiation of the deception paradigm (DDP) before transitioning to the CIT paradigm for deception detection. However, most existing fMRI-based CIT studies focused on the neural mechanism underpinning deception, and only a few studies have already tried to detect deception and reported a promising detection accuracy ranging from 0.84 to 1 (Ganis et al., 2011; Hsu et al., 2019; Nose et al., 2009; Peth et al., 2015). On the other hand, the emerging brain imaging-based technique, fNIRS, may be more suitable for forensic application due to its lower cost, portability, convenience, less physical restraints, and adapted to more people (Beurskens et al., 2014; Lee et al., 2014; Suda et al., 2010). Consistent with previous fNIRS studies which have proved the validation of fNIRS-based deception detection (Sai, Zhou, et al., 2014; Wang et al., 2022), the current study applied fNIRS to the CIT with a prior mock crime, and the results showed that fNIRS could effectively distinguish guilty from innocent participants with satisfactory deception detection efficiency (AUC = 0.81 with all 24 channels; or AUC = 0.86 with channel 8).

Previous studies have shown that combining multiple indicators could reduce system errors and thus enhance deception detection efficiency (Gamer et al., 2008; Klein Selle et al., 2016, 2017; Wang et al., 2022). For example, Gamer et al. (2008) found an improvement in detection efficiency by the combination of multiple autonomic indicators. Likewise, Matsuda et al., (2011) used both ERP and autonomic measurements in the CIT and found that introducing ERP data could increase the detection efficiency of autonomic-based CIT. However, another fMRI study found that combining autonomic measurements with fMRI-based CIT did not improve deception detection accuracy (Kozel et al., 2009). The current study supports the idea that combining physiological measures and brain-based fNIRS indicators could enhance deception detection efficiency in CIT with a mock crime scenario.

In conclusion, the current study successfully applied fNIRS technology in the CIT with a mock crime, resulting in a fine deception detection efficiency (AUC = 0.81 for all 24 channels; or AUC = 0.86 with channel 8). The results demonstrated fNIRS has great potential for deception detection in forensic applications due to its portability and economic advantages. By further combining behavioral and physiological indicators into the calculation, we found that multiple measurements could boost the final deception detection efficiency to 0.93. Especially, the combination of SCR, HR, RT, and fNIRS imaging data from the left MFG (BA10, channel 8), could increase the AUC to indicate a highly accurate level of deception detection (0.96). Therefore, with the combination of multiple measurements from CNS and ANS, the deception detection efficiency could reach a very high level in the concealed information test in a mock crime scenario.

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## Author Notes

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### Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Author Contributions

**Xingyu Yi:** Formal analysis; Visualization; Writing-original draft; Writing-review & editing. **Chongxiang Wang:** Software; Formal analysis; Visualization; Validation; Writing-review & editing. **Hongrui Li**: Writing-review & editing. **Genyue Fu:** Resources; Supervision; Writing-review & editing. **Xiaohong Allison Lin:** Conceptualization; Investigation; Formal analysis; Methodology Resources; Funding acquisition; Supervision; Project administration; Resources; Writing-review & editing.