TECHNICAL REPORT

nature neuroscience

Post-decision wagering objectively measures awareness

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The lack of an accepted measure of awareness has made claims that accurate decisions can be made without awareness controversial. Here we introduce a new objective measure of awareness, post-decision wagering. We show that participants fail to maximize cash earnings by wagering high following correct decisions in blindsight, the Iowa gambling task and an artificial grammar task. This demonstrates, without the uncertainties associated with the conventional subjective measures of awareness (verbal reports and confidence ratings), that the participants were not aware that their decisions were correct. Post-decision wagering may be used to study the neural correlates of consciousness.

The performance of any cognitive task, from recognizing a face to running a business, is an amalgam of many decisions. Some are made consciously and some are not. There is no agreed-upon way of determining which decisions are conscious. Simply asking people might seem a straightforward method, but they may deny awareness if the question asked does not relate to the method they think they used to reach the decision[1,2]. Numerical confidence ratings have been suggested as an alternative to verbal report but participants may underrate their confidence or withhold conscious knowledge, as they are given no motivation to reveal it[3]. Here we demonstrate that a newly created measure, post-decision wagering, in which people are offered cash rewards for revealing conscious knowledge, can be used to determine which decisions are made without awareness. We asked participants performing three very different tasks—visual discrimination in blindsight, string selection in an artificial grammar task and pack selection in the Iowa gambling task—to place wagers on the outcomes of their decisions. We found above chance performance in the tasks, but the wagers indicated a lack of awareness that the decisions were correct. By making it clear when awareness is absent, this method may help to answer one of the central questions of contemporary neuroscience: how does neural activity give rise to conscious experience?[4]

RESULTS

Blindsight

Blindsight, the ability to make visual discriminations in the absence of visual awareness, is a paradigmatic example of performance without awareness. We tested blindsight subject GY, who has lost almost his entire left primary visual (striate) cortex. From extensive previous studies, it is known that he can make many visual discriminations in his blind field despite reporting no awareness of the stimuli[5,6]. He faced a video display unit (VDU) and was instructed that on each self-paced trial either a square-wave horizontal grating pattern would be presented in his right visual field (within his scotoma) or no stimulus would be presented. The size, contrast and position of the stimuli were selected on the basis of previous experiments with GY, so that he would be expected to make present-absent decisions with an accuracy above chance, but would report no visual sensation. He was told that pattern and blank trials would be equally frequent. GY maintained fixation on a small central square on the VDU and initiated each trial by touching this square. His gaze direction was monitored throughout the experiment to ensure that he maintained central fixation during the trials. He was asked to respond ‘yes’ if he thought the stimulus had been presented and ‘no’ if he thought it had not. He then made a wager of either 50p or £1 on his choice. If his present-absent decision was correct, the amount wagered was added to his earnings. If it was incorrect, the amount wagered was deducted (see **Supplementary Methods** online).

In 200 trials in his blind field, GY correctly made 70% (141/200) of the yes-no discriminations, a rate much better than chance ($n = 200$, binomial, $P << 0.0001$; **Table 1**). Only 48% (67/141) of the correct choices in the discrimination task were followed by high wagers, a rate no better than would be expected if high wagers were made randomly (that is, 50%; binomial, $P = 0.5$). The proportion of correct responses for which a low wager was made (67% or 74/110) was significantly greater than chance (binomial, $P << 0.001$), indicating that many correct responses were ‘wasted’ with low wagers when he could have earned more money if he had been aware that he was responding correctly and wagered high. The proportion of correct responses (70%) was greater than the proportion of advantageous wagers (52% or 103/200), which are defined as either a high wager after a correct response or a low wager after an incorrect response ($\chi^2 = 5.9$, d.f. $= 1$, $P = 0.015$), consistent with a lack of awareness. As GY wagered high on

Table 1 Subthreshold stimuli in the scotoma (right hemifield)

	Correct	Incorrect	Total
High wager	67	23	90
Low wager	74	36	110
Total	141	59	200

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Received 21 November 2006; accepted 27 December 2006; published online 21 January 2007; doi:10.1038/nn1840

Table 2 Suprathreshold stimuli in the scotoma (right hemifield)

	Correct	Incorrect	Total
High wager	24	0	24
Low wager	1	0	1
Total	25	0	25

roughly half the trials, his failure to wager high on correct decisions cannot be a consequence of a general disinclination to wager high. GY's discriminability was significantly greater than zero in the visual task, but not in his wagering (as discussed below). That GY was capable of using visual information in his scotoma to perform the discrimination, yet did not maximize his winnings by consistently wagering high after correct classifications, indicates that he was not always aware that he was making correct decisions.

GY was more likely to wager high after a correct response (48% or 67/141) than after an incorrect response (39% or 23/59). This suggests that he was sometimes aware that he was making the correct decision. The proportion of trials on which he appears to have been aware of the stimulus is the difference between these two percentages multiplied by the total number of correct trials and divided by the total number of trials: 12/200 or 6%. The observed rate of correct responses (70%) is greater than the expected rate—determined by this difference plus the chance rate—of 56% or 112/200 ($\chi^2 = 3.24$, d.f. = 1, $P = 0.068$). Similar results were found when GY performed a localization task using the same stimulus (**Supplementary Tables 1–4** online). The corresponding statistic for the pooled data was $\chi^2 = 5.26$, d.f. = 1, $P = 0.022$. In summary, GY was occasionally aware of stimuli in his scotoma, which is consistent with previous findings[5], but there were also trials on which he correctly identified the stimulus without awareness.

To see how GY would wager when he was shown stimuli for which he reported awareness, we repeated the experiment with suprathreshold stimuli in his normal and blind fields. In his scotoma, we used a grating with a higher contrast ratio that elicits reports of awareness. In his normal (left) field we used the same grating as in the previous experiment. **Tables 2** and **3** show that, not surprisingly, he was correct in his discriminations with these stimuli and that he wagered in a way that maximized his winnings, betting high on almost every trial. His rate of advantageous wagering was almost identical to his rate of correct responses. When GY had the chance to make money by betting on events of which he was aware, he did so. We showed that this was also the case when GY's performance was equal in aware and unaware conditions (**Supplementary Table 5** and **Supplementary Fig. 1** online). This confirms that he failed to maximize his earnings when making correct judgments about the subthreshold stimuli because he was not aware that he had made correct discriminations.

Artificial grammar task

The artificial grammar task has been widely used to study learning without awareness[3]. In the training phase, participants are shown strings of letters and asked to remember them. In a subsequent test phase, they are told that the strings in the training phase obeyed a complex set of rules and are asked to classify new strings as obeying the rules or not. Typically participants perform the classification task better than chance, but claim to have little explicit knowledge of the rules and show little confidence in their judgments. However, the claim that this dissociation demonstrates performance or learning without awareness has not been universally accepted because of doubts as to whether verbal reports or confidence ratings are adequate measures of awareness[2,7].

Table 3 Suprathreshold stimuli in the normal (left) hemifield

	Correct	Incorrect	Total
High wager	23	1	24
Low wager	1	0	1
Total	24	1	25

Table 4 Artificial grammar task with real money

	Correct	Incorrect	Total
High wager	217	38	255
Low wager	266	79	345
Total	483	117	600

We therefore asked subjects to classify test strings as grammatical or not in the test phase of a typical artificial grammar learning experiment, and then to place a wager of either £1 or £2 on their choice. If the classification was correct, they had the amount wagered added to their earnings. If their choice was wrong, they had it deducted (see **Supplementary Methods**). The overall rate of correct classification (81%) was significantly greater than chance ($n = 600$, binomial, $P << 0.001$), indicating that learning had taken place (**Table 4**). The subjects' wagering did not take advantage of this, however. The number of high wagers following a correct choice (45% or 217/483) was not significantly greater than the chance rate (50%) or the overall rate of high wagering (43% or 255/600). The average amount that participants would have won by betting high on their correct judgments was £76, a substantial incentive. The fact that participants did not wager high on their correct classifications at a rate above chance shows that they were not aware that their decisions were correct. The proportion of correct responses when a low wager was made (77% or 266/345) was significantly greater than chance (binomial, $P << 0.001$), indicating that many correct responses were 'wasted' with low wagers (when more money could have been earned if participants had been aware that they were responding correctly and wagered high). Consistent with this, the rate of correct responding (81%) was significantly greater than the rate of advantageous wagering (49% or 296/600) ($\chi^2 = 45$, d.f. = 1, $P << 0.001$). The fact that the probability of wagering high after a correct decision (45% or 217/483) was higher than that after an incorrect decision (32% or 38/117) suggests that participants were sometimes (10% or 60/600) aware that they had made correct decisions, which is consistent with previous findings[3]. The observed rate of correct responses (81%) was greater than the expected rate, determined by this difference plus the chance rate (60% or 360/600) ($\chi^2 = 18$, d.f. = 1, $P << 0.001$), indicating that this awareness does not explain all of the above-chance performance. In a separate experiment, in which participants were aware of the grammatical rules on half of the test trials, we found that wagering accurately reflected both the presence and absence of awareness, even when performance was equal in the two conditions (**Supplementary Fig. 2** online).

The same dissociation between performance and wagering was shown in another group of participants who were asked to place wagers with imaginary money (signal detection theory measures are in **Supplementary Table 6** online). They made 68% correct choices, significantly above chance ($n = 1{,}200$, binomial, $P << 0.0001$), which showed that learning had taken place (**Table 5**). But, as in the group wagering with real money, the proportion of high wagers following correct choices (44% or 365/822) was not greater than that expected by chance or than the overall high wagering rate (46% or 557/1,200). This

Table 5 Artificial grammar task with imaginary money

	Correct	Incorrect	Total
High wager	365	192	557
Low wager	457	186	643
Total	822	378	1,200

shows that it is not necessary to use real money to demonstrate the dissociation of implicit and explicit knowledge with wagering.

The discrimination performance of the participants who stood to win real money ($n = 10$) was significantly better than that of the participants who wagered imaginary money ($n = 20$), *t*-test, $P << 0.0001$), although their wagering performance was not different ($P = 0.91$). This suggests that the incentive, the opportunity to make money, improved the performance of subconscious processes that, nonetheless, cannot be used directly to make money (via wagering). This implies that subconscious processes can be pushed to improve some types of behaviors (for example, string classification), but not others (for example, wagering), even though the desirable outcome of improving either (for example, earning more money) is the same.

Iowa gambling task

People with lesions of the orbitofrontal cortex perform well on IQ tests, memory tests, problem-solving tests and so on, but they are severely impaired in their ability to make decisions in their everyday life, often making disastrous personal and professional choices. The poor real-life decision making, with otherwise intact cognitive function, of people with orbitofrontal lesions correlates well with performance on the Iowa gambling task, suggesting that the task simulates real-life decision making[8,9]. On each trial of this task, the participant selects one of four packs of cards. The top card of the chosen pack is then turned over, revealing how much money has been won or lost. Each pack produces a variety of large and small losses and gains, but overall, two packs have a positive yield and two have a negative yield. After a period of exploration, selecting different packs unpredictably, participants consistently select the packs that have a positive overall yield. In our version of the task, participants were required to make a wager of either £10 or £20 of imaginary money after pack selection. When the top card of the chosen pack was turned over, it revealed a win or loss, expressed as a multiple of the chosen wager (see **Supplementary Methods**). Following the explanation of the task, each participant played 100 trials, selecting a pack, making a wager, seeing the result of their choice and then adding to or losing from an initial £400 of facsimile money.

Participants showed an initial period of pack exploration, followed by a preference for the positive packs (**Fig. 1a**). Advantageous wagering, defined as either a wager of £20 after choosing a positive pack or a wager of £10 after choosing a negative pack, lagged behind positive pack selection. The start of consistent positive pack selection was defined as the first trial on which the ten-trial rolling average of the probability of selecting one of the positive packs was significantly above chance and after which it never subsequently went back to chance. The first trial of consistent advantageous wagering was defined as for pack selection. Positive pack selection began on trial 40 ± 9 (mean ± s.d.). Advantageous wagering began on trial 70 ± 13. The difference between these is highly significant ($n = 12$, paired *t*-test, $P << 0.001$). Between the onset of positive pack selection and advantageous wagering, participants showed a preference for the positive packs but did not maximize their winnings by making the maximum wager, indicating a lack of awareness that they had chosen positive packs. If participants were aware of their strategy they would have consistently wagered £20 after selecting a positive pack. At the end of the experiment all participants tended to select from the positive packs and to wager high, consistent with awareness.

A previous claim by Bechara *et al.* to have demonstrated learning without awareness in the Iowa gambling task (that is, participants consistently selecting the profitable packs before they knew why they were doing so)[10] has been controversial. They used open-ended questions to establish that their participants did not know why they were choosing the advantageous packs. But when Maia and McClelland asked participants more directed, quantitative questions about the packs, they showed that participants were aware of the strategy they were using when making advantageous choices[11]. Using the post-decision wagering technique, we found that the difference between the two studies is a consequence of the influence of the different questioning styles on the participants' awareness.

We gave a second group the task described above but, in addition, on every 10th trial after the 20th trial they were asked the same open-ended questions used by Bechara *et al.* That is, they were asked to tell everything they knew about the game and how they felt about the game. Their pattern of pack selection and wagering was similar to that of the first group (**Fig. 1b**). Positive pack selection started on trial 46 ± 13 and advantageous wagering on trial 76 ± 8. Neither differs from the group who were asked no questions ($P = 0.22$ and $P = 0.19$, respectively).

A third group was asked, on every 10th trial after the 20th trial, the quantitative questions about the nature of the task used by Maia and McClelland. That is, they were asked to rate each pack on a scale from –10 to +10, to estimate the average wins, losses and net outcomes from selecting from each pack for ten trials, and to determine which pack they would continue to select from if they had to choose just one. These questions did not affect their pack selection, which was similar to the other two groups, but did affect their wagering (**Fig. 1c**). As soon as

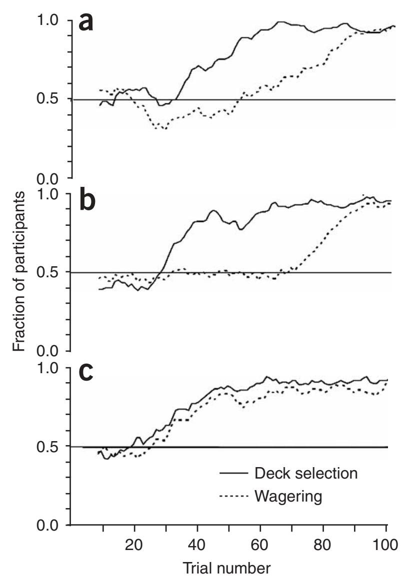

Figure 1 Performance and wagering in the modified Iowa gambling task. (**a**–**c**) The proportion of participants engaged in positive pack selection and advantageous wagering and ten-trial rolling averages for both measures are shown for (**a**) no questioning, (**b**) open-ended questioning after Bechara *et al.* and (**c**) quantitative questioning after Maia and McClelland. Advantageous wagering is plotted against positive pack selection in **Supplementary Figure 3**.

their pack selection showed a preference for the positive packs, the subjects showed a similar preference for maximizing their winnings by placing the maximum wager. Positive pack selection began on trial 36 ± 8 and advantageous wagering on trial 38 ± 8. Pack selection did not significantly differ from that of the group who were asked no questions ($P = 0.16$), but wagering did ($P << 0.0001$).

The finding that positive pack selection began before advantageous wagering if no questions were asked about the task (**Fig. 1a**) demonstrates learning without awareness. A comparison of the groups asked open-ended (**Fig. 1b**) and quantitative questions (**Fig. 1c**) shows that the form of the questions affects awareness (as measured by wagering), but not pack selection. The difference in the behavior of the two groups reconciles the findings of Bechara *et al.* with those of Maia and McClelland. With the open-ended questions used in the former study, participants performed well before they were aware of the advantageous strategy. With quantitative questions, as in Maia and McClelland's study, good performance and awareness of the beneficial strategy developed simultaneously. Subjective measures of internal states, such as asking people questions about them, can alter those states.

DISCUSSION

Our data show a double dissociation between how performance and awareness are altered. A cash incentive improved decision accuracy without affecting awareness (**Table 4** versus **Table 5**), although subjective questions that promoted introspection increased awareness without affecting decision accuracy (**Fig. 1** and **Supplementary Fig. 3** online). We were surprised by these findings because our measure of awareness, placing a wager, involves making a binary decision, just like the other decisions in each of the three tasks. This double dissociation suggests that placing a wager is a special sort of decision, one that is closely related to the process of being aware.

This close relationship between wagering and awareness is supported by the fact that participants find post-decision wagering to be more intuitive than were subjective measures. Participants in the Iowa gambling task described the questions they were asked about their knowledge as 'awkward' and 'difficult', suggesting they were not directly accessing transparent conscious states. In contrast, the post-choice wagering task was described as 'more intuitive' and even 'fun'. Similarly, the hemianope GY, who has previously performed experiments where he has been asked for confidence ratings, commented that he found confidence ratings hard to use, whereas wagering was straightforward and natural.

Subjective measures force the participants to introspect about their awareness: they index not awareness, but awareness of awareness. Post-decision wagering involves no such introspection: it measures awareness directly. Such a direct metric is a long-sought requirement for the identification of the neural substrates of awareness.

METHODS

Blindsight. The participant was a 52-year-old man, GY, who incurred a unilateral traumatic destruction of almost his entire left striate cortex at the age of 8 years that resulted in a right homonymous hemianopia with macular sparing extending 3.5° into the otherwise blind right hemifield[12]. He has residual visual sensitivity within his scotoma that enables him to detect, localize and discriminate certain transient stimuli, many of which he is unaware of—the defining characteristic of blindsight[13–16].

The stimuli were presented on a Phillips VDU (UP2799, 17-inch, vertical refresh rate of 16.6 ms) at a viewing distance of 45 cm. The screen subtended about 60° × 40°. GY started each trial by reaching out and touching a centrally placed, white start light (3° × 3°, 40 cd m^{-2}). The background luminance was 10 cd m^{-2}. After the start light was touched, a 10° × 10°, 0.4-cycle-per-degree (c.p.d.) horizontal square-wave grating appeared, with its medial edge at an eccentricity of 10° from the vertical midline. The stimulus was on for 100 ms, too briefly for the subject to move his eyes away from the start light and onto the target before it disappeared. The mean luminance of the grating was the same as that of the background. Its luminance contrast was 0.2 when the grating was on the left (suprathreshold) and either 0.2 (subthreshold) or 0.96 (suprathreshold) when it was in the blind field on the right. Eye position and eye movements were monitored continuously via an infrared camera that provided an image of the left eye, with a prominent specular reflection of the fixation square, on a VDU directly in front of one of the experimenters. Four blocks of 50 trials were performed. No feedback on the accuracy of the subject's judgments or the amount won was given during the experiment.

Artificial grammar task. Thirty students from the University of Oxford, mean age 22 ± 6 years, were recruited via e-mail postings. Ten performed the real-money experiment and 20 performed the imaginary-money experiment. An equal number of each sex performed each experiment.

Participants performed the two-grammar artificial grammar task[3,17,18]. During the training phase, participants were instructed to remember as much as possible about 45 strings that were each shown for 5 s. The strings were made up of the letters M, T, V, R and X, were between 3 and 8 letters long, and obeyed one of two sets of rules (grammar A or B). Before the test phase, participants were told that each of the strings they had seen obeyed a complex set of rules and that they were now going to be asked to determine whether new strings obeyed those same rules. During the test phase, all participants were tested on the same 60 test items, consisting of an equal mixture of grammar A and B items. For participants trained in grammar A, the grammar A test items were the grammatical items and the grammar B test items were the non-grammatical items, and vice versa for participants trained in grammar B. For each of the test strings, participants were asked to decide whether the string was grammatical or not and to make a wager of either £1 or £2 on each classification for the real-money group or £10 or £20 for the imaginary-money group. They would win or lose this amount depending on whether their classification was correct or incorrect.

Iowa gambling task. Thirty-six students were enrolled, six males and six females in each of the three groups. The mean age of participants was 22 ± 5 years. No compensation was offered for participation.

A variation of the Iowa gambling task was used, in which participants selected cards from four packs of cards for pretend cash rewards[10]. Participants sat in front of four packs of cards that were identical in appearance, except for their labels A, B, C and D. They were told that the game involved a long series of pack selections and wagers (there were 100 trials), and that the goal was to earn as much money as possible. Participants were given £400 in facsimile money (as 40 notes worth £10 each). They were informed that each trial would consist of (i) a pack selection, (ii) a wager of either £10 or £20 of pretend money and (iii) the turning over of one card from the selected pack to reveal the yield as a multiple of the wager. Participants were informed that they were free to switch between packs at any time, and as often as desired. Every card yielded a win (of either 2 × the wager for packs A and B or 1 × the wager for packs C and D). Some cards had a loss coupled with the win. The net outcome of choosing from either packs A or B was a loss of five times the average wager per ten cards (referred to as negative packs), and the net outcome of choosing from either packs C or D was a gain of five times the average wager per ten cards (referred to as positive packs).

To determine the effect of different modes of questioning on pack selection and wagering, we performed the experiment on three separate groups of participants. After selecting a pack, the first group was asked only to place a wager (wagering-only group). The second group was given open-ended questions about their strategy, using the same questions as Bechara *et al.* every 10th trial after the 20th trial. This group was asked to communicate everything that they knew about the game and to report how they felt about the game. The third group was questioned quantitatively, using the same questions as Maia & McClelland every 10th trial after the 20th trial. This group was asked to rate each pack on a scale from –10 to +10, to estimate the average wins, losses and net outcomes from selecting from each pack for ten trials and to determine which pack they would continue to select from if they had to choose just one.

Note: Supplementary information is available on the Nature Neuroscience website.

ACKNOWLEDGMENTS

N.P. was supported by a Rhodes Scholarship and A.C. by the UK Medical Research Council.

AUTHOR CONTRIBUTIONS

All three authors contributed to the execution of the experiments and the writing of this manuscript.

COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

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