Unconscious determinants of free decisions in the human brain

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There has been a long controversy as to whether subjectively 'free' decisions are determined by brain activity ahead of time. We found that the outcome of a decision can be encoded in brain activity of prefrontal and parietal cortex up to 10 s before it enters awareness. This delay presumably reflects the operation of a network of high-level control areas that begin to prepare an upcoming decision long before it enters awareness.

The impression that we are able to freely choose between different possible courses of action is fundamental to our mental life. However, it has been suggested that this subjective experience of freedom is no more than an illusion and that our actions are initiated by unconscious mental processes long before we become aware of our intention to act[1–3]. In a previous experiment[1], electrical brain activity was recorded while subjects were asked to press a button as soon as they felt the urge to do so. Notably, their conscious decision to press the button was preceded by a few hundred milliseconds by a negative brain potential, the so-called 'readiness potential' that originates from the supplementary motor area (SMA), a brain region involved in motor preparation. Because brain activity in the SMA consistently preceded the conscious decision, it has been argued that the brain had already unconsciously made a decision to move even before the subject became aware of it.

However, these intriguing experiments have left a number of controversial questions open[4–6]. First, the readiness potential is generated by the SMA, and hence only provides information about late stages of motor planning. Thus, it is unclear whether the SMA is indeed the cortical site where the decision for a movement originates[7] or whether high-level planning stages might be involved in unconsciously preparing the decision[8], as was seen in studies on conscious action planning[9–12]. Second, the time delay between the onset of the readiness potential and the decision is only a few hundred milliseconds[1]. It has been repeatedly argued that potential inaccuracies in the behavioral measurement of the decision time at such short delays could lead one to misjudge the relative timing of brain activity and intention[3–6]. Third, does any leading brain activity indeed selectively predict the specific outcome of a choice ahead of time? To rule out the idea that any leading activity merely reflects unspecific preparatory activation[13], it is necessary to study free decisions between more than one behavioral option[11,14].

Here we directly investigated which regions of the brain predetermine conscious intentions and the time at which they start shaping a motor decision. Subjects who gave informed written consent carried out a freely paced motor-decision task while their brain activity was measured using functional magnetic resonance imaging (fMRI; see **Fig. 1** and **Supplementary Methods** online). The subjects were asked to relax while fixating on the center of the screen where a stream of letters was presented. At some point, when they felt the urge to do so, they were to freely decide between one of two buttons, operated by the left and right index fingers, and press it immediately. In parallel, they should remember the letter presented when their motor decision was consciously made. After subjects pressed their freely chosen response button, a 'response mapping' screen with four choices appeared. The subjects indicated when they had made their motor decision by selecting the corresponding letter with a second button press. After a delay, the letter stream started again and a new trial began. The freely paced button presses occurred, on average, 21.6 s after trial onset, thus leaving sufficient time to estimate any potential buildup of a 'cortical decision' without contamination by previous trials. Both the left and right response buttons were pressed equally often and most of the
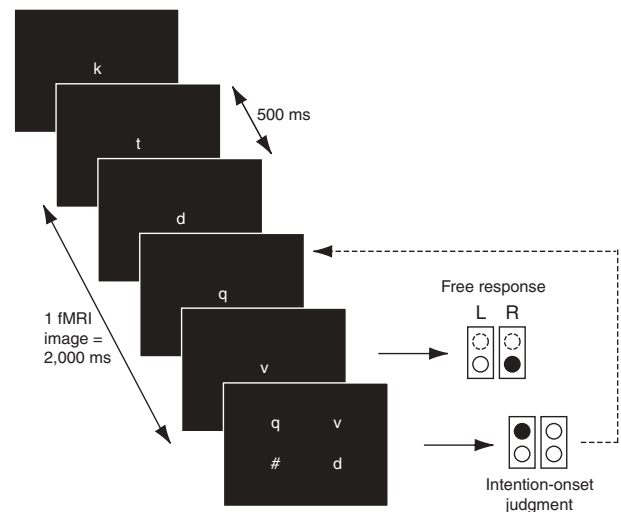

Figure 1 Measuring the onset time of conscious motor intentions. Subjects viewed a letter stream that was updated every 500 ms (shown here only for a few frames). At some point they spontaneously made the decision to press either the left or right button using their corresponding index finger (free response). Subsequently, they were presented with a response-mapping screen that instructed subjects as to which second button to press to report the time at which they consciously made the motor decision (**Supplementary Methods**).

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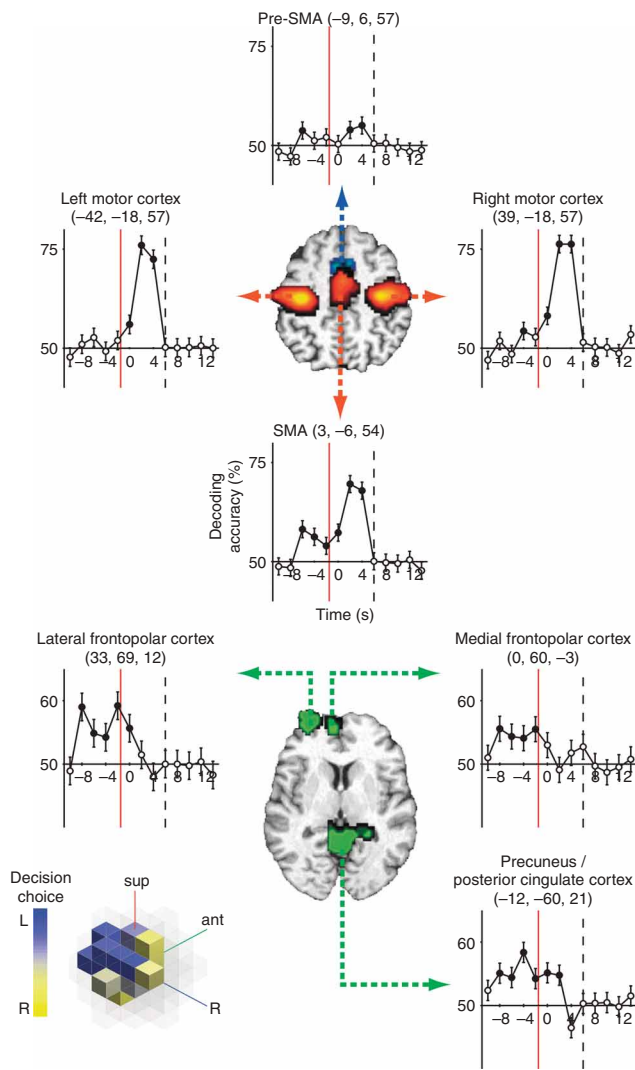
Figure 2 Decoding the outcome of decisions before and after they reached awareness. Color-coded brain areas show regions where the specific outcome of a motor decision could be decoded before (bottom, green) and after (top, red) it had been made. The graphs separately depict for each time point the accuracy with which the subject's free choice to press the left or right button could be decoded from the spatial pattern of brain activity in that region (solid line, left axis; filled symbols, significant at $P < 0.05$; open symbols, not significant; error bars, s.e.m.; chance level is 50%). As might be expected, the decoding accuracy was higher in cortical areas involved in the motor execution of the response than in areas shaping the upcoming decision before it reaches awareness (note the difference in scale). The vertical red line shows the earliest time at which the subjects became aware of their choices. The dashed (right) vertical line in each graph shows the onset of the next trial. The inset in the bottom left shows the representative spatial pattern of preference of the most discriminative searchlight position in frontopolar cortex for one subject (ant, anterior; sup, superior; see **Supplementary Fig. 9** online).

intentions (88.6%) were reported to be consciously formed in 1,000 ms before the movement (**Supplementary Methods** and **Supplementary Figs. 1–3** online).

We directly assessed how much predictive information each brain region contained about the specific outcome of a motor decision at various time points before and after it reached awareness. For each time point, we measured how much information could be decoded from local patterns of fMRI signals in various brain regions using statistical pattern recognition techniques[15] (**Supplementary Fig. 4** online). These pattern-based decoders were trained to predict the specific outcome of a subject's motor decision by recognizing characteristic local brain patterns associated with each choice. This highly sensitive approach had several advantages over previous studies. First, it allowed us to investigate any potential long-term determinants of human intentions that preceded the conscious intention far beyond the few hundred milliseconds observed over the SMA[1,14]. Second, it allowed us to separately investigate each brain region and determine how much information each region had about the outcome of a motor decision. Finally, our approach allowed us to identify whether any leading brain activity indeed selectively predicted the outcome of the subject's choice, rather than reflecting potentially nonspecific preparatory processes.

To validate our method, we first investigated which brain regions this decision could be decoded from after it had been made and the subject was executing the motor response. As expected, two brain regions encoded the outcome of the subject's motor decision during the execution phase: primary motor cortex and SMA (**Fig. 2**). Next, we addressed the key question of this study, whether any brain region encoded the subject's motor decision ahead of time. Indeed, we found that two brain regions encoded with high accuracy whether the subject was about to choose the left or right response prior to the conscious decision (threshold $P = 0.05$, family-wise error–corrected for multiple spatial and temporal comparisons; **Fig. 2**, see **Supplementary Figs. 5** and **6** online for full details). The first region was in frontopolar cortex, BA10. The predictive information in the fMRI signals from this brain region was already present 7 s before the subject's motor decision. Taking into account the sluggishness of BOLD responses, the predictive neural information will have preceded the conscious motor decision by up to 10 s. There was a second predictive region located in parietal cortex stretching from the precuneus into posterior cingulate cortex. Notably, there was no overall signal increase in the frontopolar and precuneus/ posterior cingulate during the preparation period (**Supplementary Fig. 5**). Rather, the predictive information was encoded in the local spatial pattern of fMRI responses, which is presumably why it has not been noticed before. When the statistical threshold was relaxed, several other regions of frontal cortex showed predictive information, albeit less pronounced (**Supplementary Table 1** online). We also ensured that there was no carry-over of information between trials, so that the high decoding performance preceding the motor decision by up to 10 s cannot reflect decoding related to the previous trial (**Supplementary Methods** and **Discussion** online). We also ensured that decoding was not based on movement artifacts (**Supplementary Fig. 7** online).

Finally, we also assessed the degree to which the timing of the decision could be predicted ahead of time. We found that decoding of the time decision was possible as early as 5 s preceding the motor decision, but mainly from pre-SMA and SMA, whereas in the frontopolar and parietal cortex this was only possible just before the motor decision (**Supplementary Fig. 5**). Thus, there appears to be a double dissociation in the very early stages between brain regions shaping the specific outcome of the motor decision and brain regions determining the timing of a motor decision. At later stages, right before the conscious decision, both of these regions begin to encode timing and handedness information.

Finally, to further investigate the involvement of frontopolar cortex and precuneus in selecting intentions, we investigated voluntary decisions where subjects have to decide between left and right responses at an externally determined point in time. In this case, the time when a decision is selected is under experimental control. This revealed that frontopolar cortex was already predictive during the selection of the

response, whereas the predictive information in precuneus began after the selection during the delay. This is consistent with a trend in the main experiment that showed that the information in lateral frontopolar cortex had already peaked at the earliest time point. One interpretation of this finding is that frontopolar cortex was the first cortical stage at which the actual decision was made, whereas precuneus was involved in storage of the decision until it reached awareness. Notably, the intention was selected consciously in this control experiment, suggesting that similar networks might be involved in conscious and unconscious preparation of decisions (see **Supplementary Methods** and **Supplementary Fig. 8** online for full details).

Taken together, two specific regions in the frontal and parietal cortex of the human brain had considerable information that predicted the outcome of a motor decision the subject had not yet consciously made. This suggests that when the subject's decision reached awareness it had been influenced by unconscious brain activity for up to 10 s, which also provides a potential cortical origin for unconscious changes in skin conductance preceding risky decisions[8]. Our results go substantially further than those of previous studies[1–15] by showing that the earliest predictive information is encoded in specific regions of frontopolar and parietal cortex, and not in SMA. This preparatory time period in high-level control regions is considerably longer than that reported previously for motor-related brain regions[1,14], and is considerably longer than the predictive time shown by the SMA in the current study (**Supplementary Fig. 5**). Also, in contrast with most previous studies[1,13], the preparatory time period reveals that this prior activity is not an unspecific preparation of a response. Instead, it specifically encodes how a subject is going to decide. Thus, the SMA is presumably not the ultimate cortical decision stage where the conscious intention is initiated, as has been previously suggested[7]. Notably, the lead times are too long to be explained by any timing inaccuracies in reporting the onset of awareness, which was a major criticism of previous studies[4–6]. The temporal ordering of information suggests a tentative causal model of information flow, where the earliest unconscious precursors of the motor decision originated in frontopolar cortex, from where they influenced the buildup of decision-related information in the precuneus and later in SMA, where it remained unconscious for up to a few seconds. This substantially extends previous work that has shown that BA10 is involved in storage of conscious action plans[9–11] and shifts in strategy following negative feedback[12]. Thus, a network of high-level control areas can begin to shape an upcoming decision long before it enters awareness.

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

AUTHOR CONTRIBUTIONS
J.-D.H., C.S.S., M.B. and H.-J.H. conceived the experiment. C.S.S. and J.-D.H. carried out the experiment. C.S.S. analyzed the data. J.-D.H. and C.S.S. wrote the paper.

1. Libet, B. *et al. Behav. Brain Sci.* **8**, 529–566 (1985).
2. Wegner, D.M. *Trends Cogn. Sci.* **7**, 65–69 (2003).
3. Haggard, P. *Trends Cogn. Sci.* **9**, 290–295 (2005).
4. Van de Grind, W. *Conscious Cogn.* **11**, 241–264 (2002).
5. Glynn, I.M. *Nature* **348**, 477–479 (1990).
6. Joordens, S., van Duijn, M. & Spalek, T.M. *Conscious. Cogn.* **11**, 231–240 (2002).
7. Eccles, J.C. *Arch. Psychiatr. Nervenkr.* **231**, 423–441 (1982).
8. Bechara, A., Damasio, H., Tranel, D. & Damasio, A.R. *Science* **275**, 1293–1295 (1997).
9. Koechlin, E., Basso, G., Pietrini, P., Panzer, S. & Grafman, J. *Nature* **399**, 148–151 (1999).
10. Burgess, P.W., Quayle, A. & Frith, C.D. *Neuropsychologia* **39**, 545–555 (2001).
11. Haynes, J.D. *et al. Curr. Biol.* **17**, 323–328 (2007).
12. Hampton, A.N. & O'Doherty, J.P. *Proc. Natl. Acad. Sci. USA* **104**, 1377–1382 (2007).
13. Lau, H.C., Rogers, R.D., Haggard, P. & Passingham, R.E. *Science* **303**, 1208–1210 (2004).
14. Haggard, P. & Eimer, M. *Exp. Brain Res.* **126**, 128–133 (1999).
15. Haynes, J.D. & Rees, G. *Nat. Rev. Neurosci.* **7**, 523–534 (2006).