Predicting free choices for abstract intentions

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Unconscious neural activity has been repeatedly shown to precede and potentially even influence subsequent free decisions. However, to date, such findings have been mostly restricted to simple motor choices, and despite considerable debate, there is no evidence that the outcome of more complex free decisions can be predicted from prior brain signals. Here, we show that the outcome of a free decision to either add or subtract numbers can already be decoded from neural activity in medial prefrontal and parietal cortex 4 s before the participant reports they are consciously making their choice. These choice-predictive signals co-occurred with the so-called default mode brain activity pattern that was still dominant at the time when the choice-predictive signals occurred. Our results suggest that unconscious preparation of free choices is not restricted to motor preparation. Instead, decisions at multiple scales of abstraction evolve from the dynamics of preceding brain activity.

free will | Libet | self-paced

The subjective experience that our voluntary actions are initiated in the conscious mind has been challenged by the finding that the human brain may already start shaping spontaneous decisions even before they enter into conscious awareness (1, 2). Specifically, the human brain can start preparing spontaneous movements up to several seconds before a person believes themselves to be consciously making a decision to move (1–3).

To date, such early choice-predictive signals have only been investigated for simple movement decisions (1–6). However, there are several reasons to assess whether preparatory processes also occur for higher-level, more abstract types of decisions. First, the relevance of motor decisions for understanding the neural formation and preparation of intentions has been heavily debated (7, 8), mainly because of their reduced complexity (9, 10) and the limited levels of awareness in motor control (11, 12). Second, previous studies on predictive signals for motor choices have revealed early information in prefrontal and parietal brain regions. These regions are not generally considered "motor," but they have been sporadically observed in motor preparation (13, 14). This invites the question of whether these regions provide only unconscious preparation of motor intentions or a common, task-independent network for preparing multiple types of decisions before awareness. Given the fundamentally different neural processes involved in performing motor acts and mental calculations, identifying overlap between the early choice-predictive signals would be of high relevance because it would point toward a common cerebral starting point for different types of choices.

We also aimed to address another question regarding the prediction of free choices. Previous studies (2, 4) have found early choice-predictive information in areas that overlap with the so-called "default mode" network (DMN) (15–17). For this reason, we also directly investigated the link between our choice-predictive signals and these "off-task" brain signals. Interestingly, we identified a partial spatial and temporal overlap of choice-predictive signals with activity in the DMN.

Results

We investigated the neural precursors of abstract intentions by asking participants to perform an abstract decision task in which they spontaneously and freely chose to perform either of two mental arithmetic tasks: adding or subtracting (Fig. 1 and *Experimental Procedures*). Participants were presented with a continuous stream of stimulus frames, each consisting of a letter and five single-digit numbers. They were asked to stay relaxed while monitoring the letter stream, which served essentially as a "clock" for reporting the timing of their decision. Immediately when they felt the spontaneous urge to perform either addition or subtraction, they first had to memorize the letter visible on the screen, which allowed us to reconstruct the timing of their free choice. Then they had to immediately perform the freely chosen task on the two numbers that were subsequently presented in the center of the two following frames. The third frame from the time of decision served as a response mapping screen for the calculation task, with four possible response options in the four corners: the correct addition answer, the correct subtraction answer, and two incorrect response options. The positions of these answers were randomized from trial to trial, and participants had to press a button to indicate their choice, thereby also revealing which calculation task they had chosen. After this first response, a second response-mapping screen consisting of four letters was displayed and participants indicated which of the letters was visible on the screen when they consciously made their decision. Seventeen participants performed the task while undergoing functional magnetic resonance imaging (fMRI) at 3 T, with one functional scan acquired every 2,000 ms. To identify any neural precursors that may be shaping the upcoming abstract intentions, multivariate pattern classification (18–22) was used in separate analyses to look for brain activity that could predict the content and timing of the abstract decision.

It was stressed to participants that the decision time and choice of task were completely up to them but that they should be as spontaneous as possible and execute their decision without hesitation once it was made. We ensured that all mathematical problems and their correct answers consisted of only single-digit numbers, so either task could be easily performed within the short duration given without needing much effort or preparation. Participants were familiarized with the two tasks, having gone through a prior behavioral training session. Only participants who were highly proficient in both tasks were selected for scanning. In the fMRI experiment, the inappropriate numbers were only selected on 1.2% (SE = 0.3%) of the trials, indicating that participants performed the chosen task correctly instead of making random responses. The participants' decisions could thus be reliably inferred, based on the choice of one of the two correct answers. For the appropriate responses, participants randomly (Fig. S1) selected between adding (51.9% of trials; SE = 2.0%) and subtracting (48.1%; SE = 2.0%) with equal probability ($t_{16} < 1$). Given that the four response options were randomly arranged, the specific motor response was
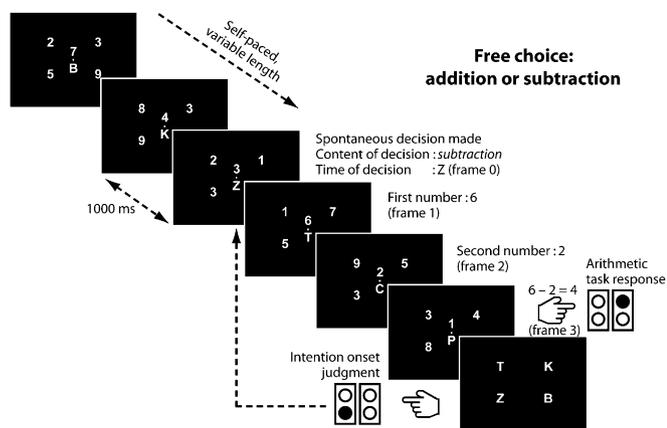
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Fig. 1. Measuring the onset and content of spontaneous abstract intentions. A trial began with a continuous series of stimulus frames refreshed every second, each consisting of a central fixation point, a letter below it, a single-digit number above it, and four single-digit response options, one in each corner. Immediately when participants felt the spontaneous urge to perform either adding or subtracting, they first noted the letter on the screen (frame 0 relative to time of decision). The chosen arithmetic task was then performed on the numbers presented above the central fixation in the next two stimulus frames (frames 1 and 2). The response options for the numbers in frames 1 and 2 were randomly presented in the four corners of the subsequent stimulus frame (frame 3): the correct addition answer, the correct subtraction answer, and two incorrect response options. Participants selected the correct answer for the chosen task by pressing one of four corresponding buttons, thereby revealing the content of their abstract decision. After the response was given, four letter options were presented from which participants selected the letter presented at frame 0, thereby revealing the time of conscious decision.

uncorrelated to the choice of task. Therefore, any information regarding the content of the decision that was decodable from brain activity could not possibly be a result of covert motor preparation. In 97.4% (SE = 0.5%) of the trials, participants indicated that the decision was made three frames before the response; that is, in frame 0, showing that they followed the task execution sequence exactly as instructed. On average, participants made a spontaneous decision 17.8 s (SE = 1.8 s) after trial onset, resulting in 12.2 (SE = 0.8) decisions per experimental run. This long delay facilitated the search for unconscious neural

precursors of the decision while avoiding contamination from the preceding trial.

We first investigated which cortical regions contained predictive information about the outcome of the abstract decision to perform addition or subtraction, and whether such information was available before or after the decision reached conscious awareness. For each discrete point from 8 s before to 18 s after the decision (14 points, each 2 s), and in different regions across the whole brain, independent classifiers were trained to distinguish between the spatial patterns of brain activity related to the two choices (adding and subtracting). The accuracy with which each independent classifier could predict the specific choice revealed whether a particular cortical region contained information related to the content of the intention at a specific point in time. This method has previously been shown to be highly sensitive in decoding simple motor intentions and in uncovering the flow of information in task preparation (2, 23).

We found that up to 4 s before the conscious decision, a medial frontopolar region ($P < 0.00005$ uncorrected, 5-voxel cluster threshold, 59.5% accuracy) and a region straddling the precuneus and posterior cingulate ($P < 0.00005$ uncorrected, 5-voxel cluster threshold, 59.0% accuracy) began to encode the outcome of the upcoming decision (Fig. 2). During this early phase, the overall signal in both regions did not show any significant change from baseline ($t_{16} < 1$), nor was there any significant difference between addition trials and subtraction trials ($t_{16} < 1$), suggesting that the information was encoded in the fine-grained spatial pattern of activation, rather than any global increase or decrease in neural activity (Fig. S2). We ensured that this early information was not a result of carry-over of information from the previous trial (SI Text S1).

We also looked for brain areas that encoded the decision after it was made, during the task preparation and execution phase. The task choice could be decoded from the angular gyrus 4 s after the time of the conscious decision (Fig. 2, *Right*; $P < 0.00005$ uncorrected, 5-voxel cluster threshold, 64.2% accuracy). Increase in information began as early as 2 s postdecision and reached statistical significance at 4 s postdecision. Taking into account the hemodynamic delay, this means that the angular gyrus probably began to encode the task choice around the time of conscious decision. This likely reflected the preparation followed by actual performance of the arithmetic task, as the angular gyrus has been found to be involved in the retrieval of overlearned arithmetic facts from memory (24, 25). As expected, there was also a global increase in blood oxygen level–dependent (BOLD) signal in the angular gyrus, peaking around 4–6 s after the decision was made
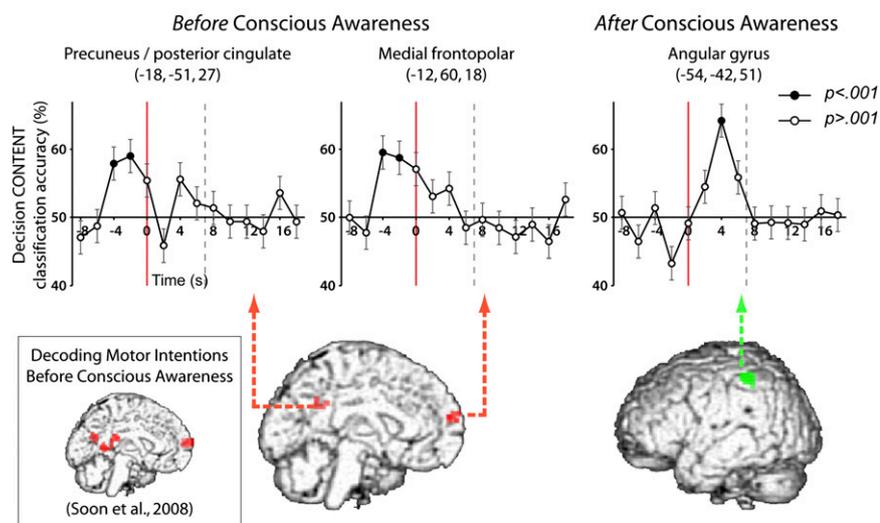
Fig. 2. Decoding the outcome of abstract decisions before and after they reach conscious awareness. Projected onto the medial cortical surface are brain regions that predicted the outcome (red) of the abstract decision before it was consciously made (MNI coordinates). *Inset* shows similar results for the decoding of free motor decisions before conscious awareness in our previous study (2). The lateral surface shows the region that encoded the outcome of the decision after it became conscious. Line graphs depict for each cortical region the accuracy with which the abstract decision to perform addition or subtraction could be decoded at each time (error bars, SE; chance level, 50%). The vertical red line indicates the point of conscious decision, and the vertical gray dashed line indicates the onset of the next trial. Given the hemodynamic delay, information available at 0 s would have been a result of neural activity occurring a few seconds earlier. Please note that none of the points below chance level was statistically significant and should thus be attributed to random fluctuation.

(Fig. S2). However, no significant difference between the two arithmetic tasks was found, even when thresholds were relaxed ($P < 0.001$ uncorrected), indicating again that the choice of task was encoded in the local detailed spatial patterns of activation, rather than the global activation magnitude.

We also used additional searchlight analyses to investigate the neural encoding of motor responses. As expected, the movement could be decoded from bilateral motor cortices and supplementary motor area (SMA), 6–10 s after the abstract decision was made (Fig. S3). Please note that this delay includes the time to complete the calculation task plus the hemodynamic delay. Importantly, these motor regions did not encode the abstract intention (Figs. S2 and S3). In our previous study (2), SMA also had choice-predictive information for motor intentions, albeit later than the parietal and frontopolar cortex. However, it was not possible here to decode the abstract intention from activity patterns in SMA at any time before or after the decision (Fig. S2). In return, the cortical regions that encoded the abstract decisions here did not encode the motor response at any time (Fig. S3), providing further evidence for a dissociation between preparation of mental calculation and motor processing.

As in a previous study (2), we also assessed the prediction of the timing of the decision (as opposed to the specific choice for adding or subtracting). This is referred to as when-versus-what decisions (26, 27). First, we identified brain regions containing early information about the timing of the upcoming decision. Classifiers were trained to distinguish the functional activity between five different points occurring from −8 to 0 s before a decision was made (see *Experimental Procedures* for full details). This information was found to be encoded in the pre-SMA, extending into the SMA and rostral cingulate zone ($P < 0.00005$ uncorrected; 5-voxel cluster threshold; 31.4% accuracy; chance level, 20%; Fig. S4), as reported previously for simple motor intentions (2). In contrast, the medial frontopolar and posterior cingulate/precuneus regions that encoded the content of the decision did not contain predictive information about the timing of the decision ($t < 1$). Next, we explored how accurately the timing of each decision could be predicted before it was consciously made on a trial-by-trial basis. Classifiers were trained to identify a combination of spatial and temporal brain activity patterns occurring in the pre-SMA region from −4 to 0 s before participants made a conscious decision. By detecting when this pattern occurred during each trial, we were able to accurately predict the exact time that participants were going to make a decision before they had made any behavioral response (71.8%; SE = 1.6%; *Experimental Procedures*).

Finally, we investigated how the predictive signals were related to activity in the task-negative DMN. This was done for two reasons: First, brain regions with choice-predictive information are in close anatomical proximity to regions of the DMN (15–17, 28), thus raising the question of whether they reflect a similar underlying mechanism. Second, high levels of DMN activity are typically observed during off-task periods (17, 28, 29); that is, during in-between periods in which participants are busy performing tasks. This raises the question of whether DMN activity is also high in the period preceding the free decision. Although this would not constitute final evidence, it could nonetheless lend further support to the notion that participants are not busy thinking about the upcoming decision during this period.

The DMN was identified with standard techniques using group-level independent components analyses (ICA) (30), and its average time course was extracted (Fig. 3 and Fig. S5; see *Experimental Procedures* for details). The same analysis was also applied to data from an earlier experiment involving free motor decisions for comparison (2). In both experiments, a typical frontoparietal DMN profile was observed (Fig. S5). To formally assess the spatial overlap between choice-predictive regions and the DMN, we performed a conjunction analysis (Fig. 3A). In the abstract intention task, there was a partial overlap with DMN in anterior medial prefrontal cortex. For the previously published motor task (2), there was a partial overlap with DMN in medial parietal cortex. Please note that it has been repeatedly shown that successful
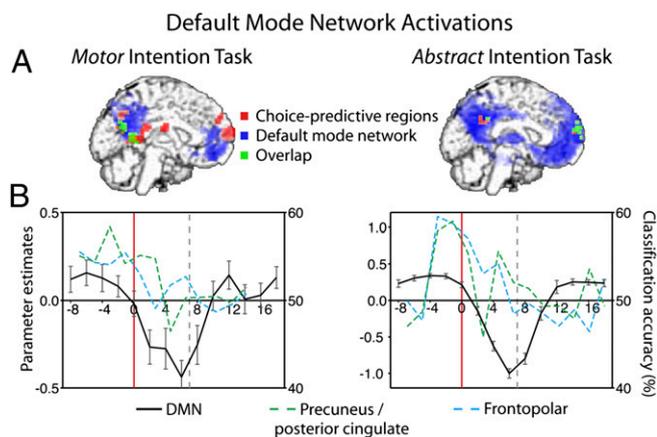
Fig. 3. Changes in overall default mode network activity for spontaneous motor and abstract intentions. (A) For both motor (*Left*) and abstract (*Right*) tasks, the DMN (blue; $P < 0.0001$) and choice-predictive (red; $P < 0.0001$) regions are projected onto the medial cortical surface, with overlapping voxels rendered in green. Please note that volume rendering projects regions from different depths onto the medial plane. (B) Activation time courses of the DMN (black line, left axis) are plotted together with the classification accuracies for precuneus/posterior cingulate (green dotted line, right axis) and frontopolar cortex (cyan dotted line, right axis). For both motor (*Left*) and abstract (*Right*) tasks, the default mode activity and the predictive information peaked roughly around the same time before conscious decision. The DMN during this early preparatory phase still resembled typical off-task or "resting" period activity, whereas parietal and prefrontal signals already encoded the upcoming choice.

pattern classification does not depend on whether a brain region shows a net positive (or negative) change in magnitude (2).

We also directly compared the time courses of default mode activity and early predictive information and found that the default mode activity and the predictive information peak roughly around the same time (Fig. 3B). The main difference was that the default mode activity began to rise earlier and lasted longer. The comparable peak time of DMN and choice-predictive information is interesting because it means that the DMN exhibits off-task-like behavior, whereas parietal and prefrontal signals already have information about the outcome of the next choice.

Discussion

Our results show that regions of medial frontopolar cortex and posterior cingulate/precuneus encode freely chosen abstract intentions before the decisions have been consciously made. Previously, a similar network of regions was reported to be involved in the unconscious preparation of motor intentions (2). In contrast, in the current experiment, the intended "action" was a nonmotor, abstract mental operation. Importantly, the randomized response mapping ensured that the motor output used to indicate the arithmetic answer was independent of, and did not contain any information about, the abstract decision made. In addition, these regions did not encode the motor response at any time before or after the conscious decision, even when the behavioral response was made. Thus, by fully dissociating high-level intentions from motor preparation and execution, our current findings provided direct evidence that the medial frontopolar and precuneus/posterior cingulate regions were involved in the formation of high-level intentions for voluntary actions in general. This also confirmed that the frontoparietal network previously reported was indeed involved in the formation of free intentions per se (2), rather than motor preparation. In future studies, it should be possible to enhance the sensitivity for smaller differences between informative brain regions by directly comparing motor and calculation tasks in the same participants.

Closer to and after the point of conscious decision, other regions involved in the actual execution of the specific voluntary action began to encode the intention. In the case of a simple motor

action, this was the motor system, including SMA and bilateral primary motor cortices (2, 5). For the abstract mental arithmetic task reported here, this was the angular gyrus, involved in the retrieval of overlearned arithmetic facts from memory (24, 25). These areas were only involved in the execution of specific tasks and did not encode intentions in general.

Previous studies have also shown that abstract decisions can be decoded from the medial frontopolar cortex, but only when these decisions were consciously maintained during a delay period before execution (31, 32). Thus, it has remained unclear whether the same regions were also involved in the unconscious formation of voluntary intentions or merely store the decisions after they have been consciously formed. In the current study, participants were not cued to make decisions at specific points in time but were allowed to make decisions spontaneously. By asking participants to report when they first consciously decided, we could investigate what happened in the brain before the decisions were consciously made. We found that both medial frontopolar cortex and posterior cingulate/precuneus started to encode the specific outcome of the abstract decisions even before they entered conscious awareness. Our results suggest that, in addition to the representation of conscious abstract decisions, the medial frontopolar cortex was also involved in the unconscious preparation of abstract decisions.

Both regions that encoded the content of the decision ahead of time have also been implicated in tasks involving both prospective memory (33–37) and imagining both the past and the future (36, 38–41). A possible interpretation of the current results is that these regions were involved in unconscious preparation for actions in the near future (40). It remains unclear whether both conscious and unconscious representations are subserved by the exact same neural substrates within these regions or whether they are separable at a finer scale. Future studies could address this question by verifying whether mutual classification between unconscious and conscious decision representation is possible. If they do share common neural substrates, then it should be possible to use classifiers trained on unconscious decision representation to decode consciously maintained decisions and vice versa.

At present, the specific functional roles of the frontopolar and precuneus/posterior cingulate regions in the formation of free decisions are not fully understood. Interestingly, medial frontopolar and posterior cingulate cortex have also been implicated in other types of decision making involving rewards, rather than "random" and "free" choices (42–47), and in tracking the subjective values of the rewards (48, 49). In most studies of decision making, participants are typically asked to decide between different alternatives that are seldom as balanced as in the current experiment. The choices are often biased by prior feedback (31) or reward characteristics such as reward type, reward level, or reward timing (45, 47, 48).

An important finding was that regions that predicted the content of the decision (adding or subtracting) did not predict the exact timing of the decision. Rather, this information was found in the pre-SMA, which has also been shown to be involved in the generation of self-initiated and self-paced motor actions in experiments in which the timing of decisions was not explicitly measured (1, 2, 5, 50–57). Taken together, when decision time is unconstrained and self-paced, unspecific activity builds up in this region over a few seconds before the decision for a voluntary action, whether motoric or abstract, is triggered. When different alternatives are available, the specific choice is shaped by activity in other regions such as the frontopolar and precuneus/posterior cingulate. Combining both sources of information about intention content and timing may provide a promising approach to understanding the neural mechanisms underlying voluntary actions.

Consistent with our findings, there is increasing evidence that prior fMRI signals can be used to predict certain upcoming mental states: Spontaneous generation of motor intentions (2) and abstract intentions (as here) can be predicted a few seconds before conscious decisions are made, and behavioral errors can be predicted up to 30 s before they occur (58). Although predictive fMRI signals have to be interpreted carefully (59), there is evidence suggesting that they could reflect low-frequency local field potentials (60, 61). Moreover, other studies using electrical recordings have also found early predictive signals. In their original EEG study, Libet et al. (1) reported the onset of the readiness potential to occur a few hundred milliseconds before the conscious motor intention. In a more recent study using single and multiunit depth electrodes, Fried et al. (5) found that in some cases, the firing rates of certain medial frontal neurons could start changing up to a few seconds before the conscious decision is made (see figure S3e in ref. 5), lending support to our earlier (2) and current fMRI findings.

It is interesting that mental calculation, the more complex task, had less predictive lead time than a simple binary motor choice in a previous study (2). This could tentatively reflect a general limitation of unconscious processing in the sense that unconscious processes might be restricted in their ability to develop or stabilize complex representations such as abstract intentions. It is also worth noting that both studies showed the same dissociation between cortical regions that were predictive of the content versus the timing of the decision. This implies that the formation of an intention to act depends on interactions between the choice-predictive and time-predictive regions. The temporal profile of this interaction is likely to determine when the earliest choice-predictive information is available and might differ between tasks.

There was a partial spatial overlap between the choice-predictive brain regions and the DMN. Interestingly, the state of the DMN during the early preparatory phase still resembled that during off-task or "resting" periods. This lends further credit to the notion that the preparatory signals were not a result of conscious engagement with the task (17, 62, 63). Furthermore, the spatial and temporal overlap hints at a potential involvement of the DMN in unconscious choice preparation.

To summarize, we directly investigated the formation of spontaneous abstract intentions and showed that the brain may already start preparing for a voluntary action up to a few seconds before the decision enters into conscious awareness. Importantly, these results cannot be explained by motor preparation or general attentional mechanisms. We found that frontopolar and precuneus/posterior cingulate encoded the content of the upcoming decision, but not the timing. In contrast, the pre-SMA predicted the timing of the decision, but not the content.

Experimental Procedures

Participants. Thirty-four healthy, right-handed participants (15 men; age range, 19–31 y) participated in a behavioral selection test in which they performed a voluntary abstract intention task (*Experimental Procedures, Behavioral Paradigm*). Twenty-two participants (12 women; age range, 22–31 y) who spontaneously showed balanced choices were selected to perform the same task while fMRI was conducted. Of these individuals, 4 participants were subsequently excluded from group analyses because of excessive movement, and another was excluded for biased intention selection (did not select subtraction at all in one run; *Experimental Procedures, Behavioral Paradigm*).

Behavioral Paradigm. Participants spontaneously and freely decided to perform either of two abstract intentions: adding or subtracting. A continuous stimulus stream was presented from the start of each trial period, 1 frame/s without gap. Each stimulus frame consisted of a consonant below a central fixation point, a single-digit number above it, and four single-digit answer options, one in each corner (Fig. 1).

Participants were asked to relax as they passively observed the letter stream. The order of presentation of letters was randomized under the constraint that there were no repetitions within a sequence of eight consonants. Immediately when they first became conscious of the spontaneous urge to perform either addition or substraction, participants noted the letter presented on the screen (frame 0). It was stressed to participants that the time and choice of task were completely up to them but that the task should be executed without hesitation once the decision was made. The arithmetic task selected was then performed on the number presented above the central fixation from the subsequent two stimulus frames (frames 1 and 2). Because the problem appeared only after the decision was made, and participants had to remember the letter presented

when the decision was made, they could not choose when to perform a task by selecting particular numbers. The response options for the numbers in the earlier two frames were randomly presented in the four corners of the third stimulus frame: the correct addition answer, the correct subtraction answer, and two inappropriate response options (32).

Participants selected their answer by pressing one of four corresponding buttons, using either their left or right index or middle fingers. Having two inappropriate response options ensured that participants performed the chosen intention properly and did not simply press a random button. Because both problems and answers involved only single-digit numbers, both adding and subtracting operations could be performed within the short span of time given. There was a 3-s gap between the point of conscious decision and the point of response during which the intention was conscious but entirely covert; that is, there was no motor response. This long gap thus alleviated concerns that the ability to judge the time of decision accurately may be biased by motor preparation, execution, and resultant effects. This was a problem in the original Libet paradigm (1) that many subsequent studies had tried to address (3, 64–69). After the first response was given, the screen went blank for 1,000 ms. Then four letter options were presented: the letter presented at the point of conscious decision (frame 0), the two letters immediately before it, and the letter immediately after it. They were shown for 1,000 ms in a randomized configuration in the four corners of the stimulus frame, from which participants selected the letter by pressing the corresponding button (2). On the basis of the timing of the first response, the stimulus frame during which the conscious decision was made could already be inferred, but having an explicit behavioral response provided additional confirmation and also ensured that the participants performed the task exactly as instructed. The screen then went blank again for 1,000 ms before the next trial period began with the presentation of a new stimulus stream.

Before the fMRI experiment, a behavioral selection test was conducted to select participants who met a set of criteria and to familiarize them with the task. It was important that the number of instances of both abstract intentions were roughly balanced to avoid biased sampling. To measure how balanced participants were in their choices, a bias index comparing the total number of "addition" trials (A) with the total number of "subtraction" trials (S) was calculated using the formula $(A − S)/(A + S)$. However, asking participants to balance their choices both would have required that they kept track of the distribution of intentions and would have affected their spontaneity, perhaps even encouraging preplanning of choices. Instead, participants were explicitly told that they did not have to balance their choices. To increase the chances of getting approximately balanced choices during the fMRI session, only participants who spontaneously showed balanced choices in the behavioral selection test were selected. Participants were also asked to stay as relaxed as possible when the stimulus stream began and to refrain from initiating actions too quickly. This served two purposes: The first was to let their mental activity settle down to a stable state, so that any build-up of neural activity before the conscious decision could be clearly observed, and the second was to minimize the overlapping of hemodynamic responses from different trials, so as to facilitate unambiguous interpretation of the BOLD signal before the conscious decision. Participants who were too hasty and made decisions in less than 10 s on average during the behavioral selection test were also excluded from the fMRI experiment. Participants were never told of these selection criteria throughout both behavioral and fMRI experiments.

Scanning Protocol and Data Preprocessing. A Siemens 3T Magnetom scanner was used to acquire echo-planar image (EPI) volumes with 30 slices at a resolution of 3 × 3 mm, with a slice thickness of 2 mm with a 1-mm gap, covering prefrontal, parietal, and most of temporal cortex (repetition time, 2,000 ms; echo time, 30 ms; field of view, 192 × 192 × 90). Ten runs of 152 fMRI volumes were acquired for each participant. A 46-slice whole-brain EPI image was also acquired to facilitate spatial normalization.

fMRI data were preprocessed using SPM2 (www.fil.ion.ucl.ac.uk/spm). After discarding the first two images to allow for magnetic saturation effects, the remaining functional images were then realigned. The whole-brain EPI image was spatially normalized to the Montreal Neurological Institute (MNI) EPI template. The resultant transformation matrix was subsequently used to spatially normalize the decoding accuracy maps.

General Linear Model Modeling and Decoding. A general linear model was estimated for each functional run. Because this paradigm involved self-initiated voluntary action, we did not expect the shape of the BOLD time course to fit the standard stimulus-response hemodynamic profile. Thus, we used a finite impulse response (FIR) predictor to model the BOLD signal (45). A set of 14 FIR regressors were used to model each trial type (adding or subtracting), covering a time range from 8 s before until 18 s

after the conscious decision (a functional scan was acquired every 2 s). In addition, trials with inappropriate responses for either the arithmetic problem or the decision time were modeled separately as error trials. Each of the two button presses were modeled separately as involving either the left or right hand by convolving with a standard Gaussian hemodynamic response function and were entered into the general linear model as covariates.

The parameter estimates from the FIR regressors for addition and subtraction trials were then subjected to multivariate pattern classification using a searchlight approach to search for predictive neural activity in an unbiased fashion (2, 20, 32) (see *SI Text S2* for details). Independent linear support vector machine (SVM) classifications were performed for each searchlight (3-voxel radius) to assess the amount of intention-related information present [10-fold cross-validation; Library for SVM (LIBSVM), www.csie.ntu.edu.tw/~cjlin/libsvm] (70). Good classification implied that the local cluster of voxels spatially encoded information about the participant's specific current intention. The whole procedure was repeated for each of 14 time points (8 s before to 18 s after conscious decision) to reveal the temporal flow of intention-related information across the cortex.

Further decoding analyses were conducted to assess the degree to which the timing of the decision, rather than its outcome, could be predicted. First, multiclass pattern classification was performed to identify cortical areas that contained early predictive information about when participants would decide to perform adding or subtracting. For each searchlight, a multiclass SVM was trained to classify which of five time bins (−8 to 0 s) a particular vector of parameter estimates came from. Correct identification of the time bin before the time of conscious intention indicated that it was possible to predict how much later the conscious intention will occur. (Given the delay in the hemodynamic response, the EPI signal occurring at 0 s should have come from neural activity occurring a few seconds earlier.) This yielded five maps of local classification accuracies for each participant: one for each time point before the conscious intention. A one-way ANOVA with five levels, one for each time point, revealed that the pre-SMA contained early predictive information about the timing of the upcoming decision (t-contrast based on all five time points, family-wise error correction for multiple comparisons, and 50-voxel cluster threshold; Fig. S4). This was then used to define the region of interest for the next stage of the analysis, in which we tried to predict on a trial-by-trial basis when each decision was going to be made, using brain activity occurring before the decision became conscious. To maximally exploit available information relevant to decision timing, we combined information from spatial and temporal dimensions to perform a spatiotemporal classification analysis (71). The aim was to identify the spatiotemporal pattern of activation immediately preceding the conscious decision against spatiotemporal vectors that were created from other time windows. The previous analysis indicated that the three times immediately preceding the conscious decision (−4 to 0 s) were most informative about decision timing. For each trial, preprocessed EPI signals, rather than parameter estimates, from every three consecutive time points and all of the voxels within the pre-SMA region of interest were concatenated into a spatiotemporal vector. If we could accurately identify the last vector within the trial, made up of time points −4 to 0 s, we would be able to predict that the participant was making a decision that would result in a behavioral response 3 s later. All trials were randomly divided into 4 sets for each participant. For each of 4 cross-validation cycles, 3 sets were used to train a support vector classifier (radial basis function) to distinguish the target vector (−4 to 0 s) from vectors of other points (nontargets). To avoid biased sampling during training, the same number of target and nontarget vectors were randomly selected. Every spatiotemporal vector from the remaining data set was then classified as a target (−4 to 0 s) or nontarget (other times). This allowed us to assess how accurately the exact time a conscious decision was going to be made could be predicted beforehand.

A second-level analysis was then performed on a voxel-by-voxel basis to determine how well decoding could be performed on average across all participants from each time and each position in the brain. For this purpose, individual decoding accuracy maps were spatially normalized to the MNI EPI template. These spatial images of local decoding accuracy were entered into a one-way ANOVA with 14 levels, one for each time point. Regions that predicted the abstract intention were identified using a t-contrast of times before the decision onset ($P < 0.00005$ uncorrected, 5-voxel cluster threshold).

Independent Components Analyses. To identify the DMN across participants, group-level ICA was performed using the Group ICA of fMRI Toolbox (GIFT) (http://mialab.mrn.org/software/gift/index.html) with the Infomax algorithm (72). The DMN was visually selected from 15 resulting components, and its time course was extracted for individual participants. The same analysis was also performed for our earlier experiment involving free motor decisions (2).

For each experiment, a conjunction analysis was used to determine the spatial overlap between the DMN and choice-predictive regions (slightly relaxed threshold of $P < 0.0001$, 5-voxel cluster threshold).

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